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PARTICLE-TRACKING ANALYSIS OF TIME-RELATED CAPTURE ZONES FOR SELECTED PUBLIC-SUPPLY WELLS IN SALT LAKE VALLEY, UTAH

By P.M. Lambert
U.S. Geological Survey

Prepared by the
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in cooperation with the
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Division of Water Rights
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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
acre-foot (acre-ft)	4,047	square meter
acre-foot per year (acre-ft/yr)	1,233	cubic meter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Chemical concentration is reported only in metric units, in milligrams per liter (mg/L). Milligrams per liter is a unit expressing the solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to 1 milligram per liter. For concentrations less than 7,000 milligrams per liter, the numerical value is about the same as for concentrations in parts per million.

Particle-Tracking Analysis of Time-Related Capture Zones for Selected Public-Supply Wells in Salt Lake Valley, Utah

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ABSTRACT

A particle-tracking analysis was done to estimate capture zones for selected public-supply wells in Salt Lake Valley. Twenty-five- and 50-year capture zones were estimated using a regional, finite-difference, ground-water flow model in conjunction with a particle-tracking program. Three sets of wells currently discharging ground water of adequate quality for public use, but located near areas of ground water with high dissolved-solids concentrations, were selected for the analysis. These included five wells in central Salt Lake Valley near the former Vitro chemical-processing site, four wells in southwestern Salt Lake Valley northeast of Copperton, and five wells in southeastern Salt Lake Valley between Midvale and Sandy. Capture zones were estimated for the wells for current average pumping and projected increased pumping. The quality of ground water within the estimated capture zones was evaluated by comparing the extent of the zones with the distribution of dissolved solids in the ground water surrounding the selected wells.

Results of the analysis of wells in central Salt Lake Valley indicate that most of the volume of ground water within the well's capture zones is characterized by dissolved-solids concentration of less than 500 milligrams per liter. Estimated capture zones of wells in southwestern and southeastern Salt Lake Valley contain ground water with higher dissolved-solids concentrations than ground water currently being discharged by those wells. Estimated 50-year capture zones of selected wells in southwestern Salt Lake Valley contain ground water with dissolved-solids concentrations exceeding 5,000 milligrams per liter. Estimated 50-year capture zones for wells in southeastern Salt Lake Valley, based on the simulation of projected increased pumping, indicate flow toward the wells from an area of ground water west of the Jordan River characterized by dissolved-solids concentrations exceeding 1,000 milligrams per liter.

INTRODUCTION

Salt Lake Valley is the main population and industrial center in the State of Utah (fig. 1). Maintenance of an adequate supply of water suitable for domestic use is one of the most important factors in sustaining the current population and industrial activity and in allowing for continued economic growth. State officials need detailed information concerning the occurrence and potential movement of poor-quality ground water with high dissolved-solids concentrations to anticipate and prevent migration of this water to points of withdrawal and thus to better manage development of the ground-water system. In July 1990, the U.S. Geological Survey, in cooperation with the Utah Department of Natural Resources, Division of Water Rights, began a study of ground-water flow and solute transport in Salt Lake Valley. Local municipalities and water users also participated in the study, including the Salt Lake City Corporation, Salt Lake County Water Conservancy District, Murray City, Granger-Hunter Improvement District, Taylorsville-Bennion Improvement District, City of South Salt Lake, and Kearns Improvement District. The study was done to better define the ground-water flow system and to evaluate the movement of ground-water flow; particularly the movement of poor-quality ground water in areas of withdrawal for public supply. The approach to these objectives included the development of ground-water and solute-movement computer simulations to enable planners to better understand the direction and rate at which ground water and chemical solutes move into, out of, and within this system under different stress conditions created by ground-water pumping. One of the steps toward achieving these objectives was the use of a numerical ground-water flow model in conjunction with a particle-tracking program to analyze ground-

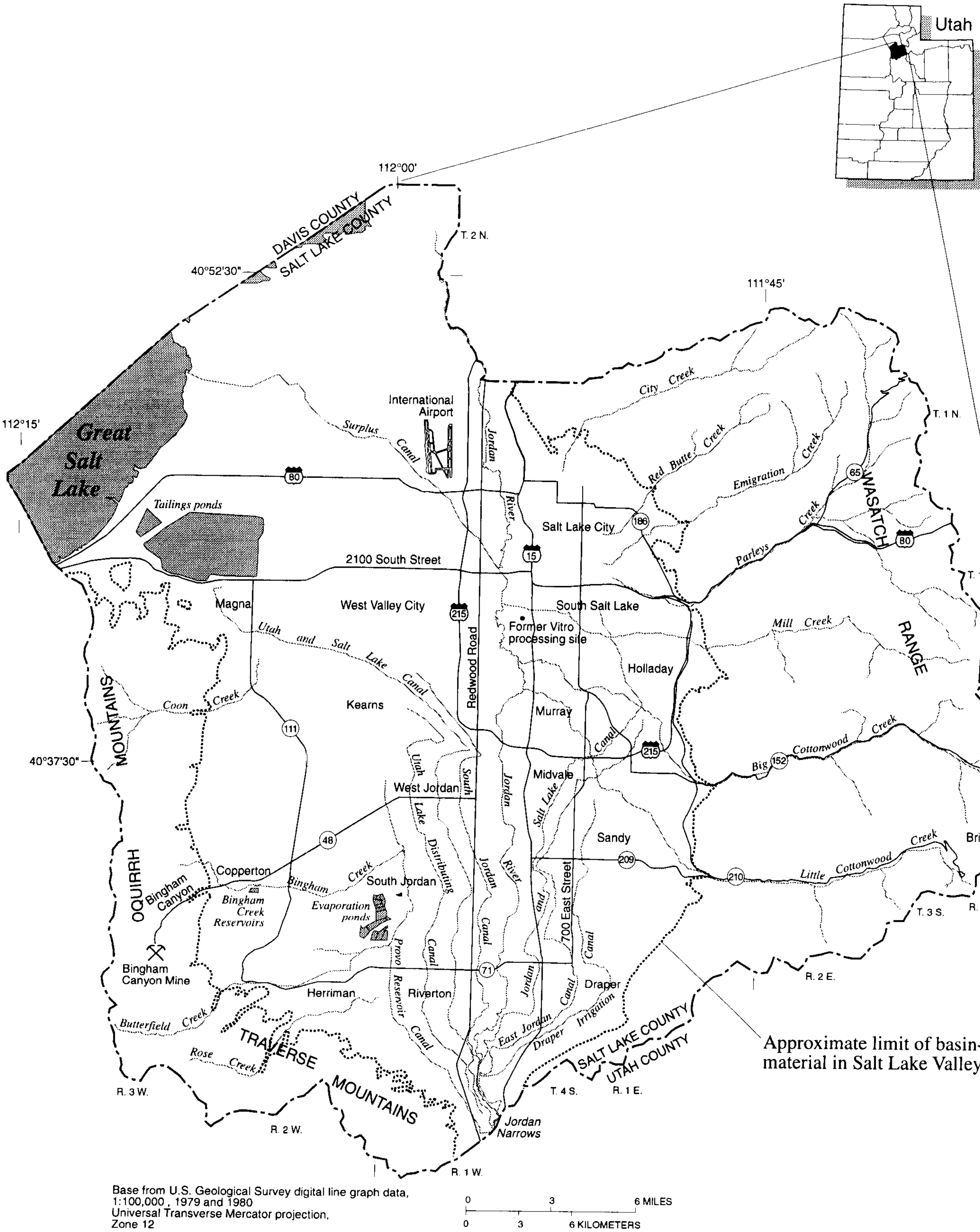


Figure 1. Location of Salt Lake Valley, Utah.

water flow in the vicinity of selected public-supply wells in the valley.

The quality of ground water in the Salt Lake Valley aquifer system is affected by the chemical quality of natural recharge, the mineralogy of the sediments that make up the aquifer, and anthropogenic contamination, and varies greatly throughout the valley. State and local water managers are interested in maintaining the quality of water currently being withdrawn by public-supply wells. Some public-supply wells in the valley that currently discharge water of adequate quality for public use are located in close proximity to poor-quality ground water. The particle-tracking method used in this part of the study provides a means of quantitatively defining pathways from these areas of poor-quality ground water to points of discharge. The resulting estimated flow paths can indicate zones of the aquifer that contribute water (capture zones) to public-supply wells and allow for consideration of the fact that the quality of the ground water in those zones could eventually affect the quality of water in the wells that withdraw water from them.

This is the fourth in a series of reports on Salt Lake Valley. The first report presented hydrologic data collected in Salt Lake Valley during 1990-92 (Thiros, 1992). The second report presented interpretations of those data and describes selected chemical properties of water and hydrologic properties of the basin-fill aquifer system in Salt Lake Valley (Thiros, 1995). The third report documents the development and calibration of a three-dimensional, finite-difference, numerical model designed to simulate ground-water flow in basin-fill material in Salt Lake Valley (Lambert, 1995).

Purpose and Scope

The purpose of this report is to document the estimation of time-related capture zones of selected wells using a regional, finite-difference, ground-water flow model of Salt Lake Valley (Lambert, 1995) in conjunction with the particle-tracking program MODPATH (Pollock, 1994). The report also includes an evaluation of the quality of ground water within each estimated zone. Three groups of public-supply wells currently discharging water of adequate quality for public use but located near areas of ground water with high dissolved-solids concentrations were selected for the analysis. Twenty-five- and 50-year capture zones were estimated for selected well sets based on the simulation of two ground-water use scenarios: (1) continued withdrawal from wells at current rates as defined by average withdrawals for 1992-93, and (2) increased withdrawal from wells from current rates to meet projected future ground-water demands. The quality of ground water within estimated capture zones was evaluated by comparing the horizontal and vertical extent of the estimated zones with the distribution of dissolved solids in the ground water surrounding the selected wells.

As with all numerical methods, the particle-tracking method used in this analysis is based on limiting assumptions. This report discusses some of the inherent difficulties in the determination of capture zones resulting from the use of a numerical representation of a complex regional ground-water flow system. The limitations of the analysis and the significance of the time-related capture zones estimated in this analysis also are discussed at the end of this report.

Hydrogeologic Setting of Salt Lake Valley

Salt Lake Valley is a structural graben filled with semiconsolidated and unconsolidated basin-fill material. The valley is surrounded by the Oquirrh Mountains on the west, the Traverse Mountains on the south, the Wasatch Range on the east and northeast, and Great Salt Lake on the northwest (fig. 1). The surrounding mountains are composed of consolidated rock with negligible primary porosity but with substantial secondary porosity in the form of fractures and solution openings (Hely and others, 1971, p. 10). Geophysical data indicate that the consolidated-rock base of the valley is an irregular surface formed by the tops of fault blocks, (Cook and Berg, 1961, p. 81) with inner-valley grabens containing, in some places, more than 4,000 ft of unconsolidated and semiconsolidated basin-fill (Mattick, 1970, fig. 6).

The basin-fill material consists mostly of sediments of Tertiary and Quaternary age and includes clay, silt, sand, gravel, tuff, and lava. The history and sequence of deposition of these sediments was described by Marine and Price (1964) as "extremely complex" because of the different mechanisms of deposition and erosion working in the valley and in the adjacent mountains throughout time. The valley received lake deposits in areas that were inundated by a series of ancient lakes, the most extensive of which was Lake Bonneville. As lakes dried, lake sediments were subjected to stream erosion, and previously inundated areas received stream-channel and flood-plain deposits.

Alluvial fans formed along the mountain fronts at canyon mouths; glacial and mud-rock flow deposits also were laid down at the margins of the valley. As lakes reappeared and filled the valley, lacustrine deposition again predominated. The changes in depositional environments in the valley as lakes formed, dried up, and reappeared has resulted in the interlayered lacustrine, alluvial, and glacial sediments that make up most of the basin fill today, with coarse-grained sediments common near the mountains and finer-grained sediments in the low-lying areas of the central and northern parts of the valley.

The basin-fill ground-water flow system in Salt Lake Valley (fig. 2) has been described by Hely and others (1971, p. 107) as consisting of (1) a confined (artesian) aquifer, (2) a deep unconfined aquifer between the confined aquifer and the mountains, (3) a shallow unconfined aquifer overlying the confined aquifer, and (4) local unconfined perched aquifers. The confined aquifer is in the central and northern parts of the valley and consists of deposits of clay, silt, sand, and gravel. In the confined aquifer, beds and lenses of fine-grained material of slight to moderate permeability tend to confine water in beds of sand and gravel. In the northern part of the valley, fine-grained sediments probably make up most of the confined aquifer. In other areas of the confined aquifer, the beds and lenses are relatively thin and discontinuous; therefore, there is appreciable movement of water between more permeable beds of sand and gravel. Overlying the confined aquifer are sediments of relatively low permeability that consist of interfingering and overlapping layers and lenses of clay, silt, and fine-grained sand of Quaternary age. Although the continuity of these sediments varies, in many areas they act as a single bed, the top of which generally lies within 100 ft of land surface. For the purpose of discussion, this bed of fine-grained sediments is referred to in this report as the shallow confining layer. Near the margins of the valley where confining sediments are absent, ground water is unconfined. The confined zone beneath the shallow confining layer and the unconfined zones near the margins of the valley make up the principal aquifer of the ground-water flow system, which is the main source of most of the ground water withdrawn from wells in the valley (Hely and others, 1971, p. 109; Waddell and others, 1987a, p. 5).

The thickness of basin-fill material of Quaternary age that makes up most of the principal aquifer ranges from 0 to 2,000 ft. Quaternary-age basin fill of the principal aquifer generally overlies relatively impermeable semiconsolidated sediments of Tertiary and pre-Tertiary age (Arnow and others, 1970, p. D257). In some areas of the valley, however, more permeable Tertiary-age basin fill containing sand and gravel yields water to wells. Tertiary-age basin fill is known to yield water to wells in the vicinity of Kearns and to the west, near Murray, and near Herriman and Riverton (Hely and others, 1971, p. 107). Water-yielding zones in Tertiary-age basin fill are included with the principal aquifer in the discussions that follow.

A shallow unconfined aquifer overlies the shallow confining layer. The aquifer is mainly composed of fine-grained sediments and in some areas of the valley cannot be differentiated from the underlying confining layer. The aquifer is the source of water for local irrigation but is seldom used to supply water for domestic or industrial purposes because it yields water slowly and generally contains water of poor quality (Seiler and Waddell, 1984, p. 2). Ground water is perched in areas where the water level in the principal aquifer is below the bottom of the shallow confining layer; thus, an unsaturated zone exists between the water table in the principal aquifer and the body of perched water above it. Areas of perched water occur east of Midvale and between Herriman and Riverton.

Recharge to the basin-fill ground-water flow system primarily is from inflow from consolidated rock at the margins of the valley, seepage from streams and canals with a water-surface altitude higher than that of the water table, infiltration of precipitation on the valley floor, and infiltration of unconsumed irrigation water from fields, lawns, and gardens. Ground water moves from primary recharge areas near the margins of the valley to the center and northern parts of the valley (fig. 2). As ground water moves from the deep unconfined aquifer beneath recharge areas into the confined aquifer, an upward vertical gradient is established. From the axial part of the valley, ground water moves upward in the confined aquifer, into and through the overlying confining layer, and into the shallow unconfined aquifer, where it is discharged mainly into the Jordan River or to drains, is used by riparian vegetation, or evaporates at land surface. Most of the discharge from the basin-fill ground-water flow system, other than discharge from wells, is through the shallow unconfined aquifer.

Present-day hydrology in Salt Lake Valley is greatly affected by municipal and industrial use of ground water. A summary of annual ground-water withdrawal from wells during 1931-68 (Hely and others, 1971, fig. 66) indicates a range from 38,000 acre-ft in 1931 to 118,000 acre-ft in 1966. The rate of with-

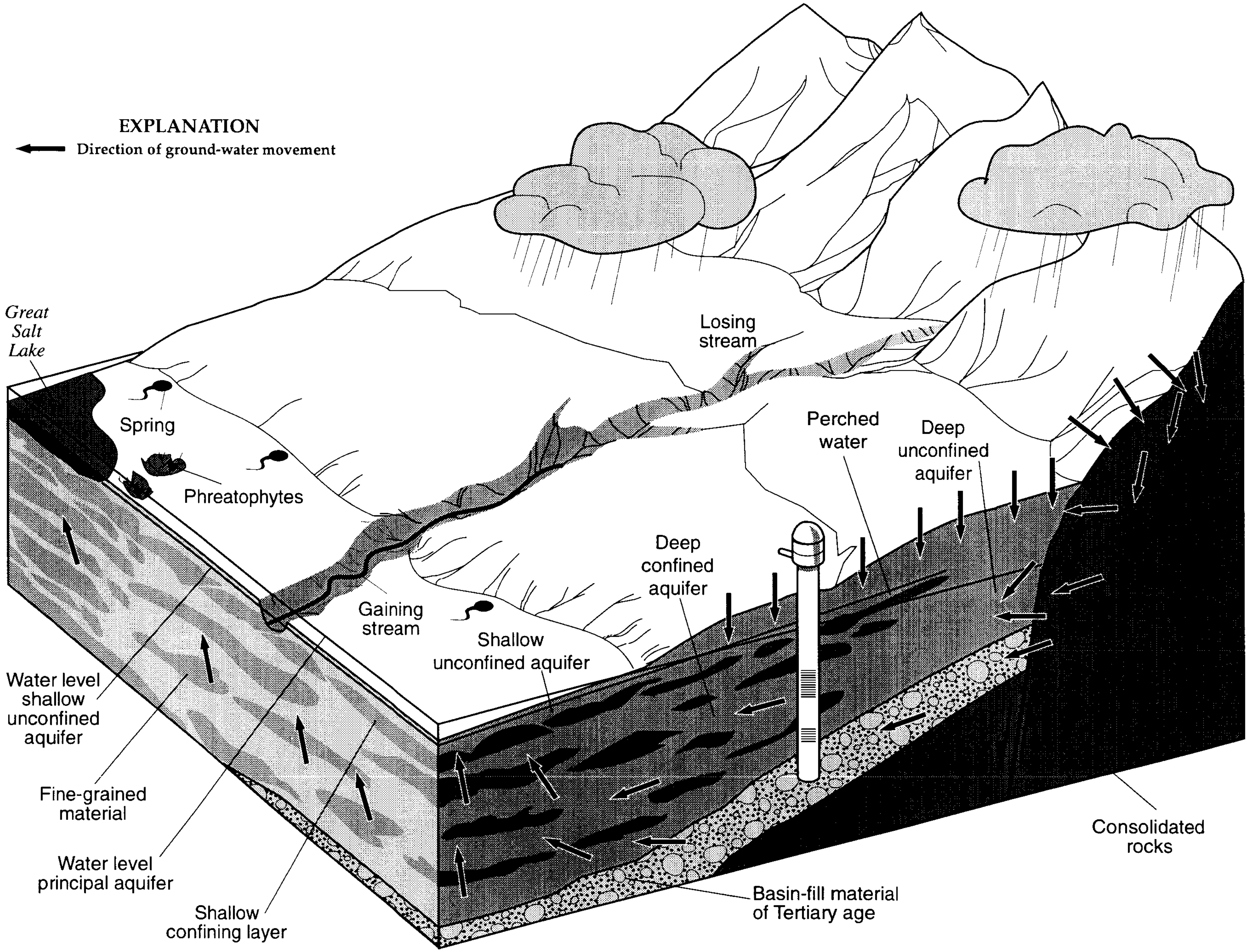


Figure 2. Generalized block diagram showing the basin-fill ground-water flow system in Salt Lake Valley, Utah. Modified from Hely and others (1971).

drawals began to level off about 1964 and averaged 107,000 acre-ft/yr during 1964-68 (Hely and others, 1971, p. 140). Increases in ground-water withdrawals during 1987-91, combined with less-than-average recharge to the ground-water flow system, have resulted in water-level declines in the southeastern part of the valley of up to 26 ft for that period (Batty and others, 1993, fig. 11).

The Concept of Time-Related Capture Zones

A time-related capture zone of a discharging well in a three-dimensional flow regime is the volumetric part of the aquifer that contributes water to a well within a selected period of time and is described by the set of all flow paths that intercept the discharging well within that period. A time-related capture zone can be visualized, as shown in figure 3, as a three-dimensional section of the aquifer extending from the well toward recharge source areas.

The characteristics of flow paths to a discharging well are affected by all geohydrologic factors that can affect the flow field around a well and include the hydrologic properties of the aquifer, the boundary conditions of the flow system, and the addition or removal of ground water at internal sources or sinks near the well. Both analytical and numerical modeling techniques have been used to simulate flow near discharging wells in order to estimate contributing areas or volumes to wells. Morrissey (1989) refers to several analytical models that are useful for the delineation of "areas of contribution" of wells, including those described in Freeze and Cherry (1979), Lohman (1979), and Todd (1980). The use of analytical methods, however, typically requires simplification of aquifer boundaries and properties. Consequently, the application of many analytical methods is valid only for steady-state flow through a homogeneous, isotropic media in a two-dimensional flow regime. The use of numerical models, although requiring more data for model construction, allows for the representation of the aquifer system in greater detail, including the simulation of three-dimensional flow. Shafer (1987) applied a numerical method based on reverse calculation of ground-water flow paths to delineate time-related capture zones around water-supply wells in a two-dimensional flow regime. Using a similar approach, Bair (1990) applied a three-dimensional numerical model of a glacial-drift/carbonate-bedrock aquifer system in conjunction with a particle-tracking program to estimate time-related "capture areas" of a municipal well field. In both cases, the use of numerical models allowed for the representation of flow in a heterogeneous and anisotropic system to be incorporated in the particle-tracking analysis.

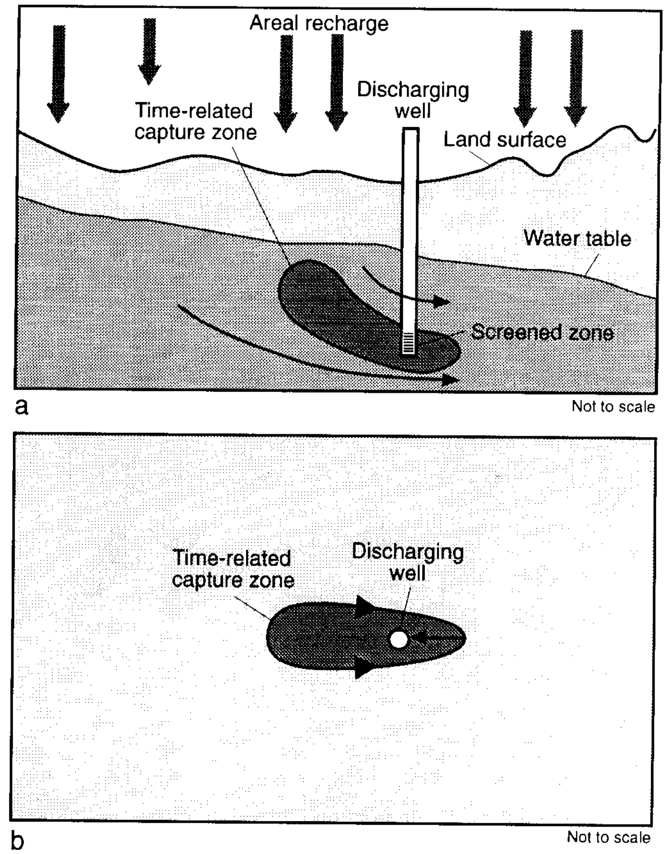


Figure 3. Schematic diagram showing time-related capture zone for a single discharging well in a simplified hypothetical ground-water system: (a) cross-sectional view, (b) map view. Adapted from Reilly and Pollock (1993, fig. 1).

The Particle-Tracking Method

The particle-tracking program MODPATH (Pollock, 1994) used in this analysis to estimate time-related capture zones of wells determines flow paths and advective travel times for specified periods of time by computing particle movements through a velocity field. The method uses intercell flows calculated in a finite-difference flow model to derive three-dimensional velocity fields within model-grid cells. Velocities are obtained by dividing volume flow rates across a cell face by the cross-sectional area of the face and the porosity of the material in the cell. The derivation assumes that porosity within the cell is constant and that each velocity component varies linearly within a cell in its own coordinate direction. Once the three-dimensional velocity distribution is derived for each cell in the flow model, the unique path of any particle in the model domain can be computed.

The program can compute particle pathlines using intercell flows computed in steady-state or transient-state finite-difference flow simulations. A steady-state simulation assumes the amount of water flowing into the ground-water system equals the amount flowing out and that no changes in ground-water storage occur. In a transient-state simulation, the amount of water flowing out of the system equals the amount flowing in plus some change in storage, and the determination of water level in the model is time dependent. A transient-flow simulation generally consists of a series of discrete time steps during which flow rates are constant. MODPATH (Pollock, 1994) uses the same tracking algorithm to compute pathlines in steady-state and transient-state simulations by taking advantage of the fact that a transient-state simulation behaves the same as a series of steady-state flow periods. For a given time step in a transient-state simulation, a steady-state velocity distribution is calculated and particle paths are computed. For each subsequent time step, a new velocity distribution is calculated and the computation of pathlines is resumed.

The tracking algorithm in MODPATH (Pollock, 1994) can determine particle pathlines either in the direction of flow or in the reverse direction by tracking particles backward along flow paths. The "backward tracking" option is useful for determining recharge source areas for localized zones of discharge, such as well fields, by placing particles in model cells that contain simulated wells and tracking them backward toward recharge source areas. This option was used exclusively during this analysis.

Pathlines computed using the particle-tracking method are accurate for the model representation of the ground-water flow system. The numerical model, however, is a simplified and idealized approximation of the actual ground-water flow system. The particle-tracking analysis provides, at best, information about how water moves in the system described by the model. The degree to which the model accurately represents the actual system must be taken into consideration when interpreting the results of a particle-tracking analysis. The limitations of the analysis that result from the numerical simulation of the ground-water flow system are discussed later in this report.

Simulation of Ground-Water Flow in Salt Lake Valley

A three-dimensional, finite-difference, numerical model of ground-water flow in the basin-fill aquifer system in Salt Lake Valley (Lambert, 1995) provided intercell flow data to the particle-tracking program. Areally, the model grid of the Salt Lake Valley flow model is 94 rows by 62 columns (fig. 4), with each model cell 0.35 mi on a side. Vertically, the aquifer system is divided into seven layers. The shallow unconfined aquifer and the underlying shallow confining layer are represented by one model layer each (model layers 1 and 2, respectively) (fig. 4). The thickness of model layers 1 and 2 is variable and roughly imitates the estimated depth and thickness of the shallow unconfined aquifer and the underlying shallow confining layer. The principal aquifer is divided into five layers (model layers 3 to 7) (fig. 4). Model layers 3 to 5 are each 150 ft thick; the simulated saturated thickness of model layer 3 may vary during problem solution. Model layer 6 is 200 ft thick. Model layer 7 ranges in thickness from 200 ft to more than 1,500 ft. The thickness of model layers 4 to 7 is not explicitly incorporated into the numerical model but is implicitly incorporated in model input defining aquifer properties of those model layers. Active cells in model layers 3 to 7 represent basin-fill material of Quaternary age in the principal aquifer and in some areas include the upper part of the underlying Tertiary unit.

Specified-flux boundaries are used in the model to simulate recharge entering the ground-water system as (1) inflow from consolidated rock in areas at the margins of the valley, (2) seepage from streams and major canals, (3) infiltration of precipitation and unconsumed irrigation water, (4) seepage from reservoirs at the mouth of Bingham Canyon and evaporation ponds in the southwestern part of the valley, and (5) underflow at Jordan Narrows. Specified-flux boundaries also were used to simulate discharge to wells, canals, and springs. A specified-flux boundary condition allows the flow rate across a given boundary to be specified as a function of location and time. Flow rates across these boundaries are specified in advance in model simulations and, thus, are not affected by simulated events in the ground-water system.

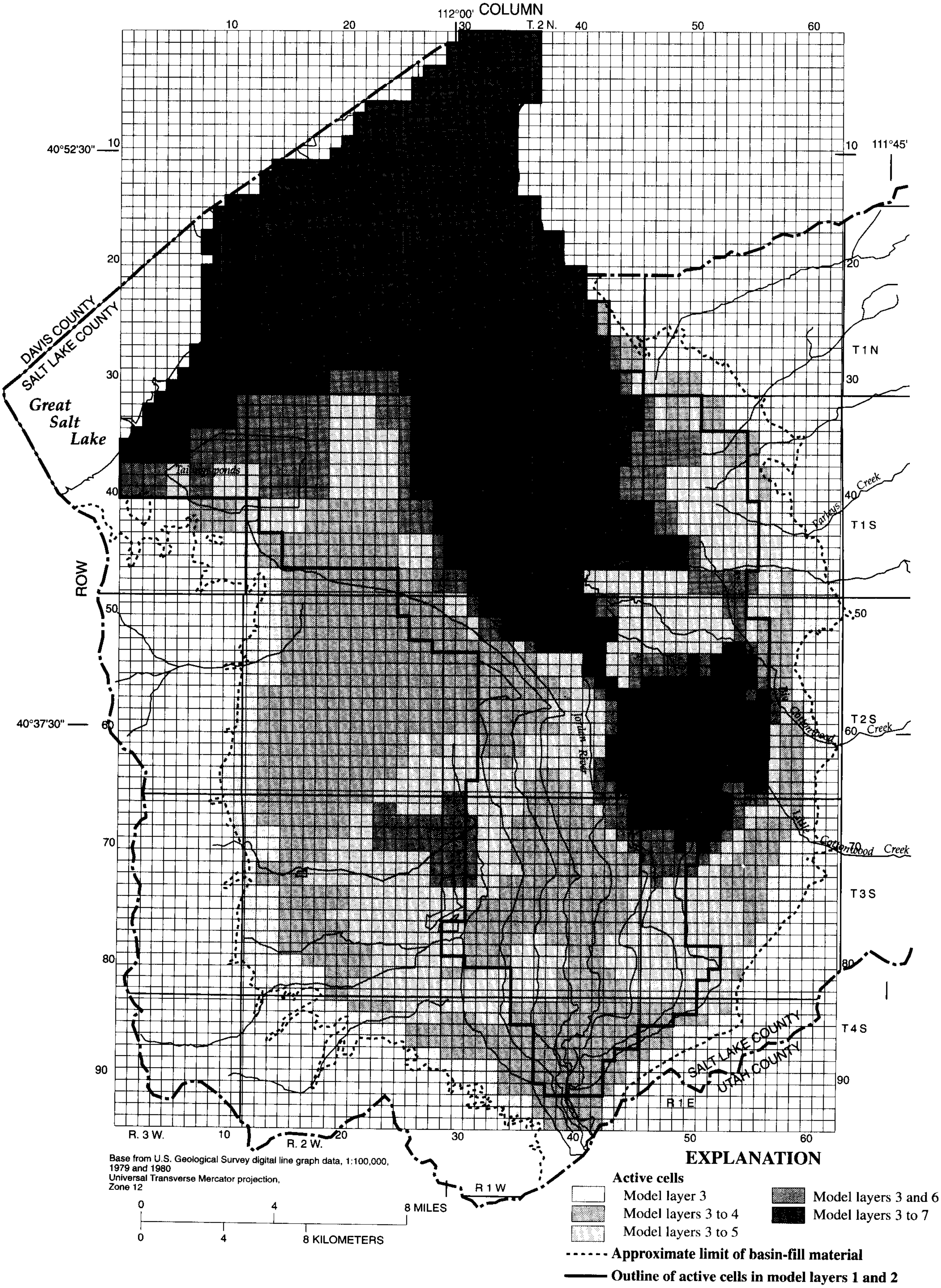


Figure 4. Grid and location of active cells in the ground-water flow model of Salt Lake Valley, Utah.

Head-dependent flux boundaries are used in the model to simulate (1) ground-water flow to and seepage from the Jordan River and the lower reaches of its principal tributaries, (2) inflow from consolidated rock at the northern end of the Oquirrh Mountains, (3) discharge from the shallow unconfined aquifer to drains, and (4) discharge by evapotranspiration. A head-dependent flux boundary allows the flow rate across the boundary surface to change in response to changes in water level in the aquifer adjacent to the boundary. Flow rate across the boundary is therefore a function of water level in the adjacent aquifer and may vary during the simulation period.

A no-flow boundary at the base of the modeled area corresponds to the contact between consolidated rock of pre-Tertiary age and basin-fill material, or to a depth in the basin fill below which sediments were assumed not to contribute substantially to the basin-fill ground-water flow system. On the west and east sides of the modeled area, no-flow boundaries correspond to the contact between the consolidated rock of the mountains and the basin fill. The northern border of the modeled area approximates a flow line and also is treated as a no-flow boundary. The shore of Great Salt Lake in the northwestern part of the modeled area is treated as a constant-head boundary representing the altitude of the lake surface.

The Salt Lake Valley flow model was calibrated to steady-state conditions for 1968 and to transient-state conditions for 1969-91 (Lambert, 1995). Development of these simulations and the ability of the model to reproduce measured hydrologic conditions during these periods is described in detail by Lambert (1995).

For the purposes of the particle-tracking analysis, the Salt Lake Valley flow model was applied to estimate hydrologic conditions during a 50-year period from 1992 to 2041 under two sets of pumping conditions. Final model-computed water levels from the 1969-91 transient-state simulation documented by Lambert (1995), representing conditions at the end of 1991, were used as the initial condition for both simulations.

The first simulation incorporated constant pumpage representing current average rates of withdrawal as defined by 1992-93 reported values (Utah Department of Natural Resources, Division of Water Rights, written commun., 1993) (table 1). The 50-year simulation period was represented using one stress period during which all external stresses on the simulated system were held constant. The stress period was divided into 20 time steps. The length of the first time step was 98 days (rounded) and was increased with advancing time by a time-step multiplier of 1.2. Time-step length was determined during development of the simulation by adjusting the length to ensure that the accuracy of the simulation was not affected by truncation error resulting from an inappropriate step size.

In the second simulation, pumpage from public-supply wells was increased from 1992-93 average rates to projected rates of withdrawal for 2025 (table 1) as estimated by Utah State University College of Engineering; Utah Department of Natural Resources, Division of Water Resources; and Bureau of Reclamation (1993), and by Utah Department of Natural Resources, Division of Water Resources (written commun., 1994) during the development of a water-demand/water-supply model for the valley. More recent estimates were obtained for wells operated by the Salt Lake County Water Conservancy District (written commun., 1994) and were incorporated in the second simulation. The simulation period from 1992 to 2023 was divided into sixteen 2-year stress periods with two time steps each. The length of the first time step was 292 days and the length of the second time step was 438 days. A single stress period divided into nine time steps was used to simulate conditions during 2024-41. The length of the first time step was 315 days and was increased with advancing time by a time-step multiplier of 1.2. Simulated pumpage from individual public-supply wells was adjusted each stress period in uniform increments from 1992-93 average rates of withdrawal in stress period 1 to projected 2025 rates of withdrawal in stress period 17. Discharge from other wells used for industrial, stock, irrigation, or domestic purposes was assumed not to change during the simulation period.

For both 50-year flow-model simulations used in the particle-tracking analysis, recharge and discharge simulated at specified-flux boundaries, other than seepage from reservoirs and evaporation ponds in the southwestern part of the valley and infiltration of unconsumed irrigation water, were specified at rates used in the 1968 steady-state simulation by Lambert (1995) representing long-term averages (table 1). Reservoirs near the mouth of Bingham Canyon and evaporation ponds east of the reservoirs that contributed recharge to the basin-fill ground-water flow system prior to 1991 had either been lined to eliminate seepage or were no longer in use by 1992; recharge from those sources was not represented in the 50-year flow-model simulations. Recharge from unconsumed irrigation water is estimated to have decreased from 1968 to 1991 (Lambert, 1995) as a result of the urbanization of agri-

Table 1. Ground-water budget for Salt Lake Valley flow-model simulations used in the particle-tracking analysis
[Data in acre-feet per year]

Budget element	Simulations for particle-tracking analysis (end of 50-year simulation period)	
	Incorporating 1992-93 average pumpage	Incorporating projected increased pumpage for 2025
Recharge from		
Consolidated rock	135,000	136,000
Irrigated fields and lawns and gardens	41,000	41,000
Precipitation	67,000	67,000
Canals	30,000	30,000
Streams and channel fill	16,000	16,000
Underflow at Jordan Narrows	2,500	2,500
Reservoirs and evaporation ponds	0	0
Jordan River and tributaries	2,000	11,000
Storage	3,600	5,500
Total (rounded)	297,000	309,000
Discharge to		
Jordan River and tributaries	98,000	72,000
Wells (total)	131,000	173,000
Public-supply	(78,000)	(120,000)
Stock and domestic	(30,000)	(30,000)
Industrial	(20,500)	(20,500)
Irrigation	(2,500)	(2,500)
Evapotranspiration	31,000	28,000
Springs	19,000	19,000
Drains	7,600	6,700
Great Salt Lake	1,300	1,200
Canals	9,200	9,200
Storage	0	0
Total (rounded)	297,000	309,000

cultural land. The decreased recharge rates for unconsumed irrigation water, estimated for 1991 in the Salt Lake Valley transient-state flow model developed by Lambert (1995) were, therefore, used in the 50-year flow-model simulations (table 1) and particle-tracking analysis.

Projected increases in pumpage for four public-supply wells in the southwestern part of the valley (table 2) were not incorporated in the second 50-year flow-model simulation. Initial simulations incorporating projected increases in pumping for these wells resulted in water-level declines near the wells of greater than 300 ft at the end of the simulation—a magnitude considered unacceptable by State water managers (Allyson T. Grandy, State of Utah Department of Natural Resources, Division of Water Rights, written commun., 1995). Instead, 1992-93 average rates of withdrawal for these wells were incorporated in both 50-year simulations.

The simulation of both average and projected increased pumpage during 1992 to 2041 resulted in substantial model-computed water-level declines in the principal aquifer relative to initial 1991 water levels (fig. 5). The simulation of constant pumpage at average 1992-93 withdrawal rates for 50 years resulted in model-computed water-level declines relative to 1991 starting water levels in most of the southern half of the valley (fig. 5a). Water-level declines computed by the model at the end of this simulation do not exceed 25 ft in most of the valley but are as much as 166 ft in the southwestern part of the valley. In the areas of largest declines in the southwestern part of the valley, 21 cells in model layer 3 were simulated as dry at the end of the 50-year simulation. Large model-computed water-level declines in the southwestern part of the valley are mainly the result of simulated withdrawals from recently constructed public-supply wells in the area and the elimination of recharge from reservoirs at the mouth of Bingham Canyon. The results of the 50-year flow-model simulation incorporating projected increased pumpage indicate model-computed water-level declines in the principal aquifer of up to 178 ft in the southwestern part of the valley and declines greater than 50 ft in the southeastern part of the valley (fig. 5b). Thirty-nine cells in model layer 3, located mainly in the southwestern part of the valley, were simulated as dry at the end of this simulation.

Water-level rises relative to initial 1991 water levels are simulated in the northern part of the valley for the 50-year flow-model simulation incorporating 1992-93 average pumpage, and in the northwestern part of the valley for the 50-year simulation incorporating projected increased pumpage. For both simulations, model-computed rises in water levels are mainly because 1992-93 average withdrawal rates for industrial wells in the northwestern part of the valley, incorporated in both 50-year simulations, were less than rates simulated in the final 4 years of the 1969-91 simulation by Lambert (1995) used to obtain initial 1991 water levels. Also, long-term average recharge rates incorporated in both 50-year simulations were greater than recharge rates simulated in the final 5 years of the 1969-91 simulation by Lambert (1995). Model-computed water-level rises in areas indicated in figure 5 were generally less than 5 ft, except in the northwestern part of the valley where computed rises were as much as 16 ft.

The simulation of projected increased pumpage in the second 50-year flow-model simulation resulted in substantial changes in flow rates at river boundaries that simulate ground-water flow to or seepage from the

Table 2. Public-supply wells in Salt Lake Valley, Utah, selected for the particle-tracking analysis

Well designation	Name	Owner	Row, column, and layers of model cells simulating well discharge	Average discharge during 1992-93, in acre-feet per year	Projected discharge in 2025, in acre-feet per year[1]
			Well set A, central Salt Lake Valley		
A1	Davis	South Salt Lake	44,44,6-7	890	820
A2	Well #1	Granger-Hunter	45,40,6-7	450	650
A3	Fairway	Taylorsville-Bennion	48,41,4	320	250
A4	Meadow Brook	Taylorsville-Bennion	48,41,4-5	1,060	1,540
A5	Lift Station	Taylorsville-Bennion	48,41,5	0	300
				2,720	3,560
			Well set B, southwestern Salt Lake Valley[2]		
B1	Barney Creek	West Jordan	66,24,4-5	970	1,410
B2	New Bingham	West Jordan	67,26,4-5	1,650	2,450
B3	Fire Station	West Jordan	68,26,4-5	1,990	3,200
B4	Well #6	West Jordan	69,24,4-6	1,960	2,840
				6,570	9,900
			Well set C, southeastern Salt Lake Valley		
C1	Oakstreet	Midvale	64,44,3-5	540	160
C2	Copperview	Sandy City	65,55,3-6	770	790
C3	Wallin	Sandy City	66,48,4-5	500	1,480
C4	City Hall	Sandy City	67,47,4	350	500
C5	Cemetery	Sandy City	68,48,5-6	775	800
				2,935	3,730

[1]As estimated by Utah State University, College of Engineering; Utah Department of Natural Resources, Division of Water Resources; and Bureau of Reclamation (1993), and by Utah Department of Natural Resources, Division of Water Resources (written commun., 1994).

[2]Projected discharge in 2025 for well set B was not incorporated in the particle-tracking analysis. Discharge in 2025 was adjusted to average 1992-93 rates in the 50-year flow-model simulations used in the particle-tracking analysis.

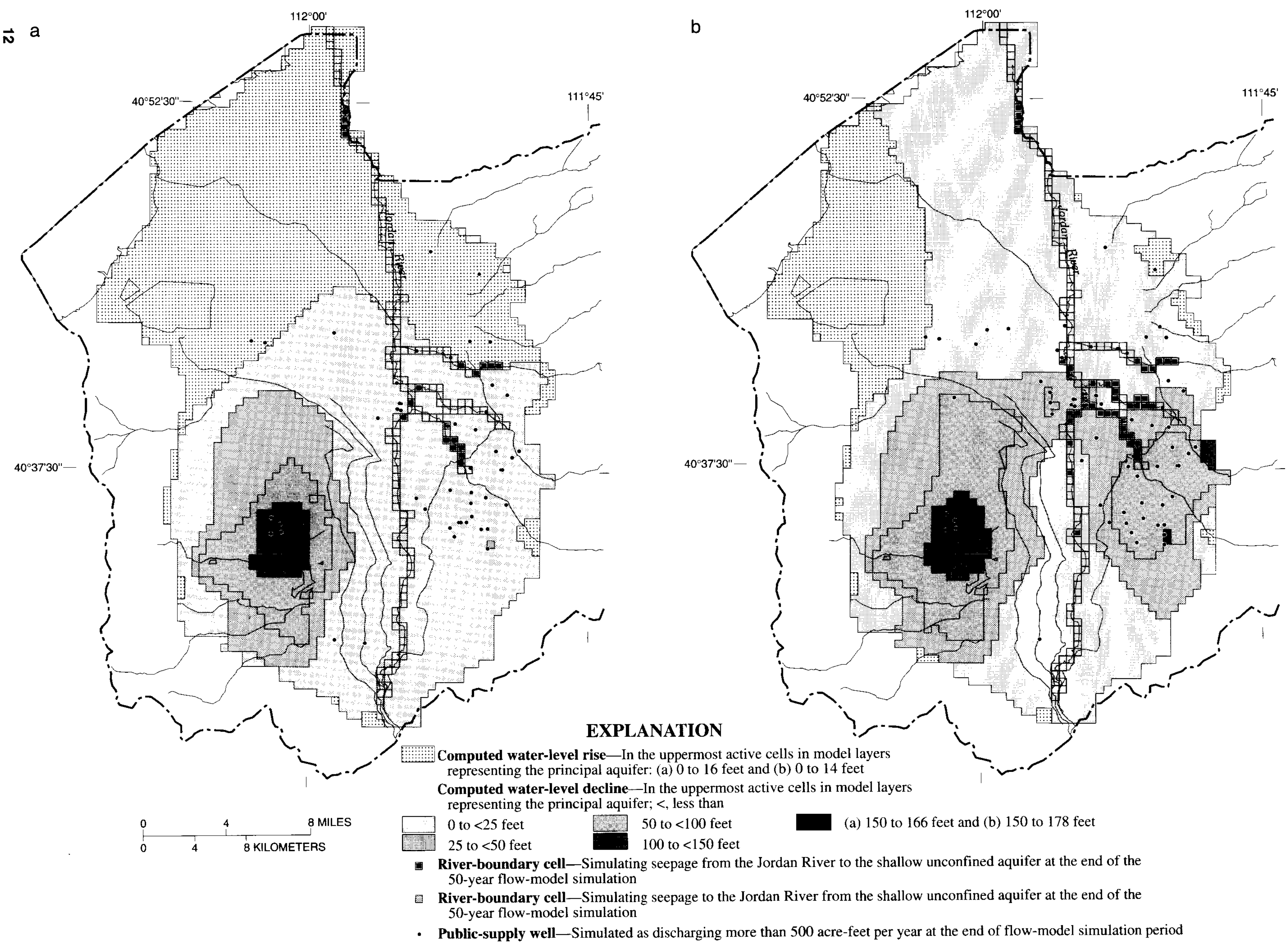


Figure 5. Model-computed water-level changes in the principal aquifer in Salt Lake Valley, Utah, from 1992 to 2041 and simulated gaining and losing sections of the Jordan River and the lower reaches of its principal tributaries based on the simulation of (a) average 1992-93 pumpage and (b) projected increased pumpage.

Jordan River and the lower reaches of its principal tributaries (table 1 and fig. 5). In the 50-year simulation incorporating 1992-93 average pumpage, the Jordan River is simulated as gaining throughout most of the valley (fig. 5a) with about 98,000 acre-ft/yr computed as discharging to river boundaries (table 1). In the simulation incorporating projected increased pumpage, the model-computed discharge to the river is reduced to about 72,000 acre-ft/yr at the end of the 50-year period (table 1) and the number of model cells where seepage from river boundaries is simulated has increased (fig. 5).

The simulated potentiometric surface of the principal aquifer computed at the end of each 50-year flow-model simulation is shown in figure 6. Ground water generally can be assumed to move perpendicular to potentiometric contours. At the end of the 50-year simulation incorporating average 1992-93 pumpage, ground water is simulated as moving from the east and west margins of the valley toward the Jordan River in the center of the valley (fig. 6a). A different flow pattern is indicated in the potentiometric surface computed on the basis of the simulation of projected increased pumpage (fig. 6b), where ground water is simulated as moving toward discharging wells in the southeastern part of the valley from the east margin of the valley and from the west under the Jordan River.

SELECTED WELLS AND THE QUALITY OF SURROUNDING GROUND WATER

Three sets of wells (table 2) located in different areas of the valley were selected for the analysis (figs. 7-9). The well sets include public-supply wells presently discharging ground water of adequate quality for public use that are located near areas of ground water with high dissolved-solids concentrations or ground water contaminated from human activities. The distribution of dissolved solids in the basin-fill aquifer system as defined by Thiros (1995, pl. 2 and fig. 12) was used in this analysis to identify public-supply wells near areas of ground water with high dissolved-solids concentrations and to evaluate the relative quality of ground-water contained in estimated capture zones. Thiros (1995, pl. 2 and fig. 12) mapped dissolved-solids concentrations in water from the principal aquifer and from shallow sediments of the overlying shallow confining layer and shallow unconfined aquifer in Salt Lake Valley. Adaptations of these maps and the locations of wells selected for the particle-tracking analysis are shown in figures 7-9. In southwestern Salt Lake Valley, Thiros (1995, pl. 2) defined the distribution of dissolved solids in the principal aquifer for two vertical intervals. The dissolved-solids concentrations in the southwestern part of the valley shown in figure 7 represent water from wells with finished intervals greater than 300 ft below land surface. The dissolved-solids concentrations for the same area shown in figure 9 represent water from wells with finished intervals from 100 to 300 ft below land surface.

Central Salt Lake Valley

Five wells in central Salt Lake Valley (table 2 and fig. 7) were selected for analysis. Total annual discharge for the well set averaged 2,720 acre-ft for 1992-93 and is projected to increase to 3,560 acre-ft by 2025 (table 2). The wells discharge from the confined part of the principal aquifer (the confined aquifer) from a zone of ground water with dissolved-solids concentrations less than 500 mg/L that extends from recharge areas at the eastern and southeastern margins of the valley (fig. 7). Dissolved-solids concentrations in ground water in the principal aquifer increase to the west and to the north of the well set (fig. 7). The poorest quality water in the vicinity of the well set is in the overlying shallow unconfined aquifer at the former Vitro chemical-processing site (fig. 8), where ground water has been contaminated from the leaching of mill tailings.

The Vitro site is located about 4 mi southwest of the center of Salt Lake City. During 1951-64, the Vitro site was used to process uranium ore for sale to the U.S. Atomic Energy Commission (U.S. Department of Energy, 1984). Although the processing plant was dismantled during 1970, the radioactively contaminated materials from the processing operations remained on the mill site until they were removed during 1985-87. Leaching of the tailings has resulted in increases of concentrations of dissolved solids and heavy metals in the ground water in the shallow unconfined aquifer beneath the site and directly west of the site.

The results of previous investigations of ground-water chemistry in the Vitro area done in the mid-1980's by the U.S. Department of Energy (1984) and the U.S. Geological Survey (Waddell and others, 1987b) indicated elevated levels of dissolved solids, chloride, sulfate, iron, and uranium in the shallow unconfined aquifer, which in the area of the Vitro site, is about 45 ft thick (Waddell and others, 1987b, fig. 10, and U.S. Department of Energy, 1993, p. 9). Measured dissolved-solids concentrations in the shallow uncon-

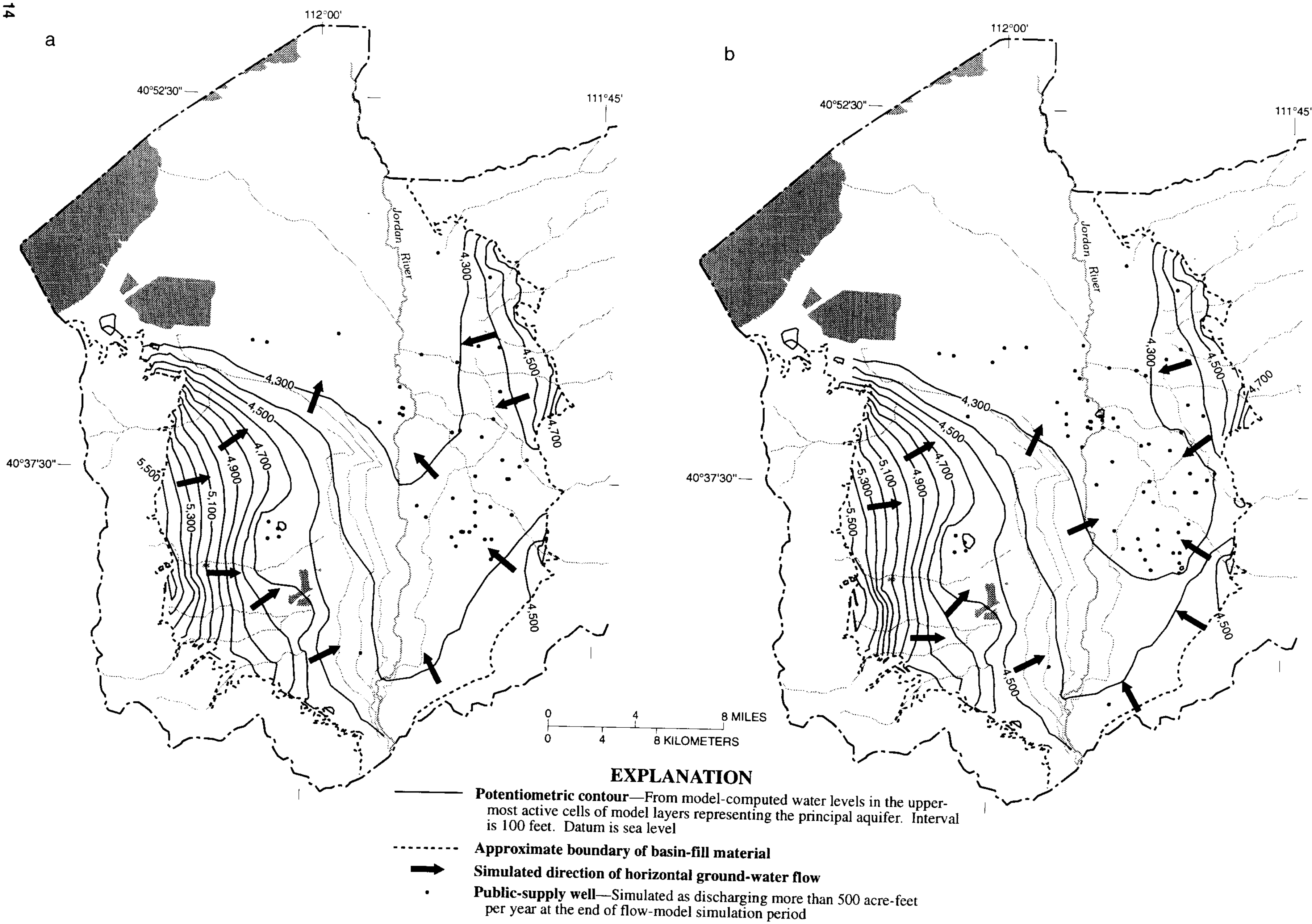


Figure 6. Model-computed potentiometric contours of the principal aquifer in Salt Lake Valley, Utah, for 2041, based on the simulation of (a) average 1992-93 pumpage and (b) projected increased pumpage.

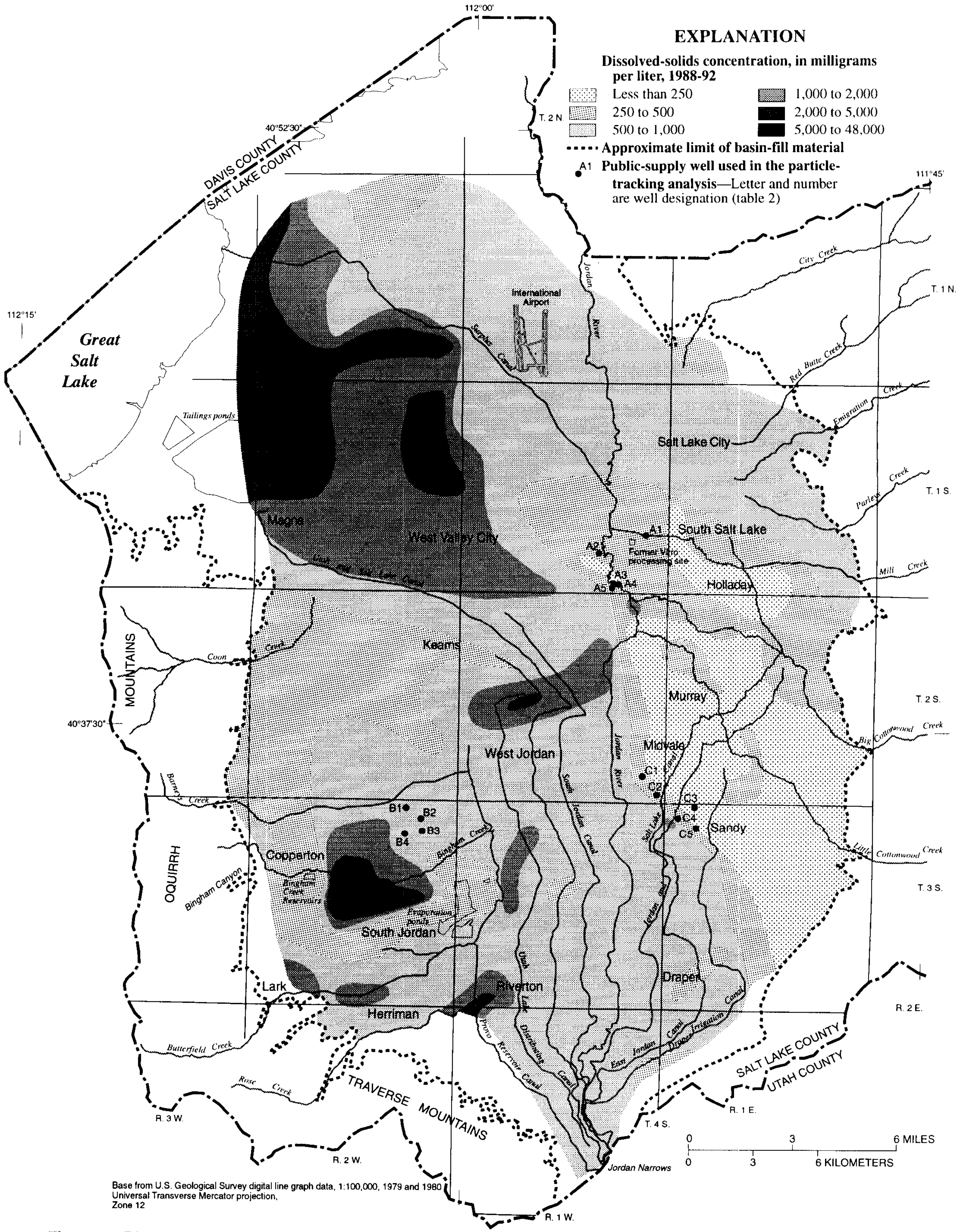


Figure 7. Dissolved-solids concentration in water from the principal aquifer in Salt Lake Valley, Utah, 1988-92. Adapted from Thiros (1995, pl. 2).

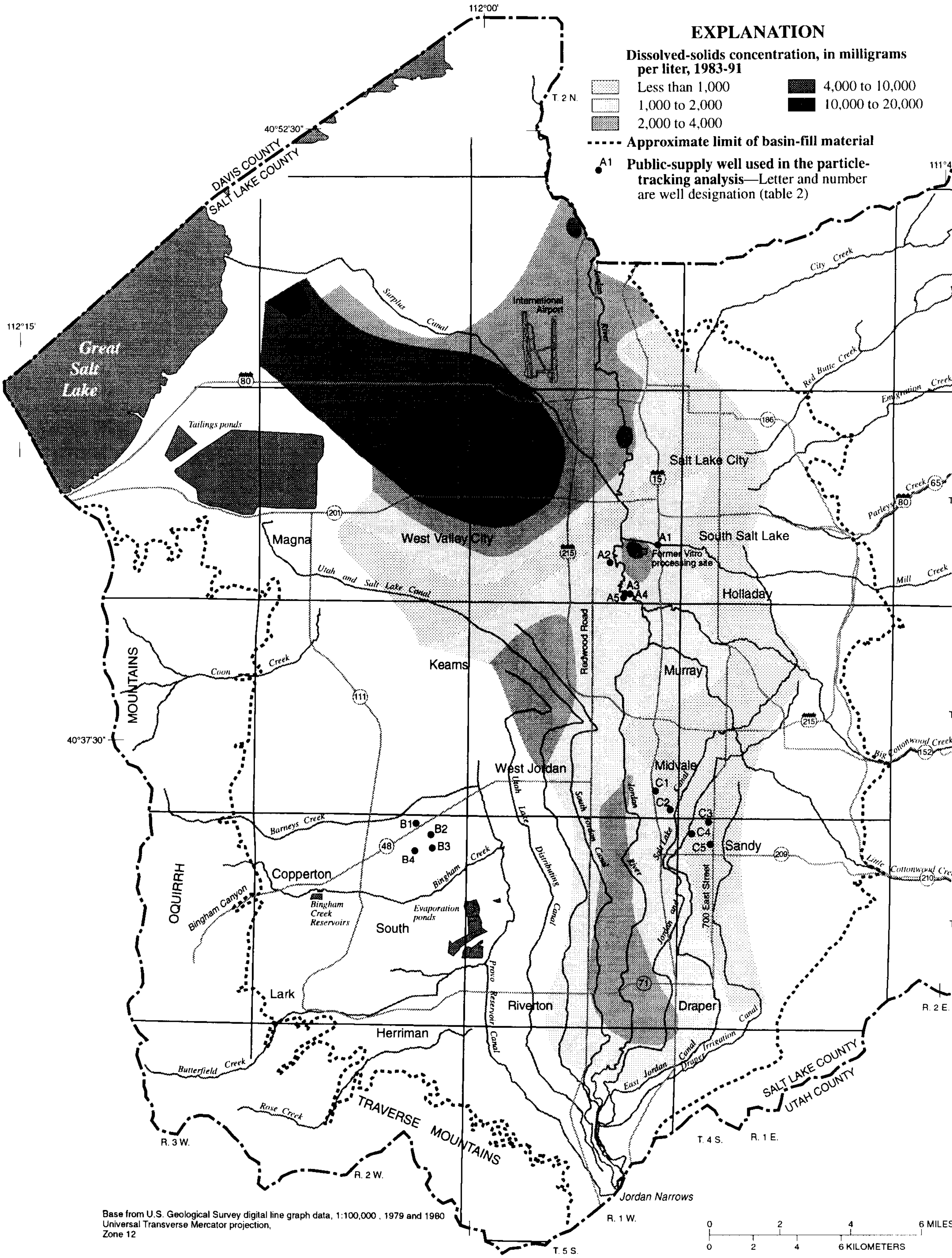


Figure 8. Dissolved-solids concentration in water from the shallow unconfined aquifer and the shallow confining layer in Salt Lake Valley, Utah, 1983-91. Adapted from Thiros (1995, fig. 12).

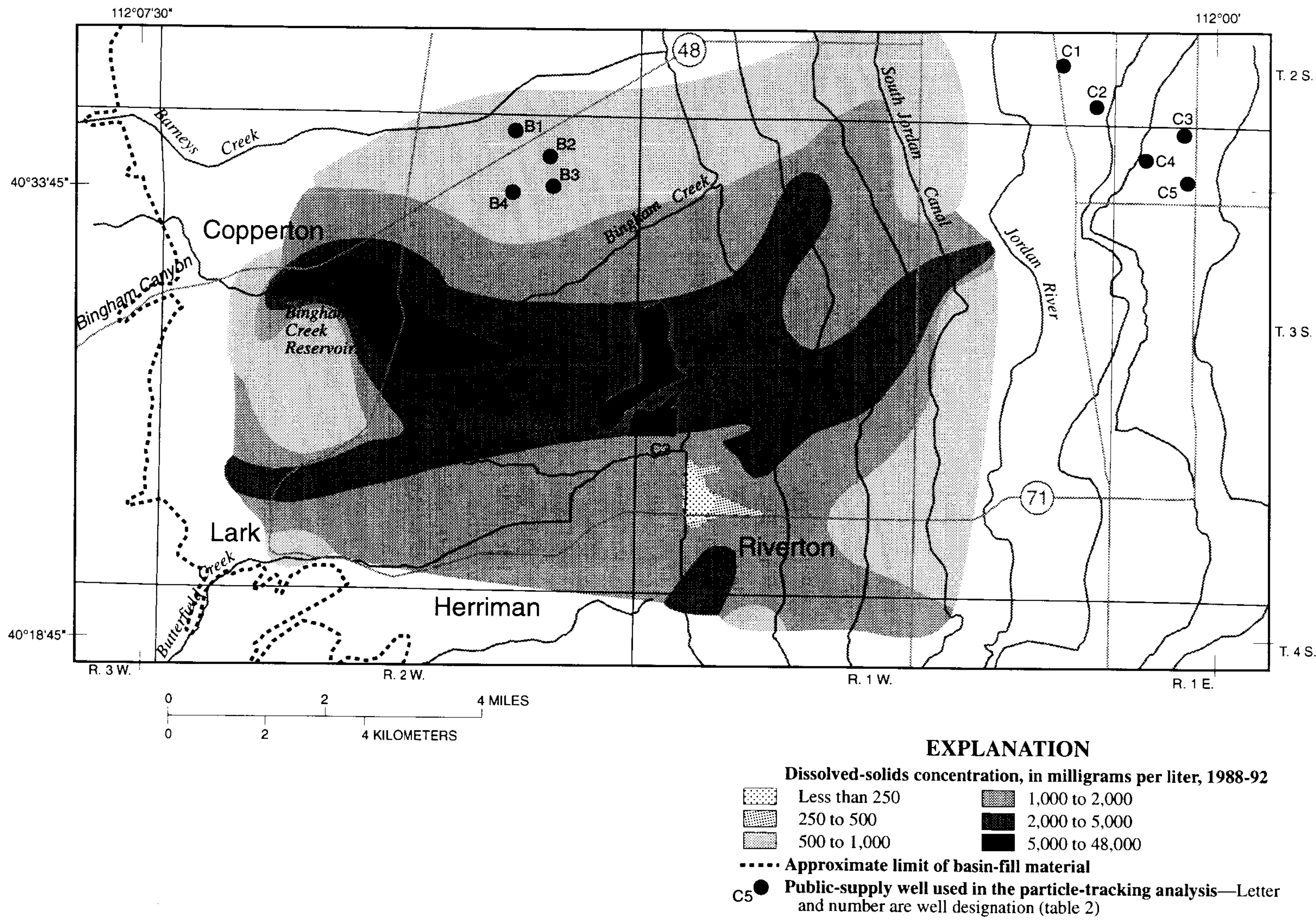


Figure 9. Dissolved-solids concentration in water from the principal aquifer within 100 to 300 feet of land surface in southwestern Salt Lake Valley, Utah, 1988-92. Adapted from Thiros (1995, pl. 2).

fined aquifer just west of the site ranged from 2,320 to 21,000 mg/L (Waddell and others, 1987b, p. 31), compared to typical background concentrations ranging from 1,000 to 2,000 mg/L (U.S. Department of Energy, 1984, p. d-37). Waddell and others (1987b, p. 31) reported that ground water sampled during 1982-83 in wells completed in the upper sediments of the confined aquifer (within 90-175 ft of land surface) below and to the west of the tailings site showed elevated concentrations of dissolved solids (fig. 10a), including chloride, sulfate, iron, and uranium, indicating possible contamination. Waddell and others (1987b, p. 34) concluded that movement of water from the shallow unconfined aquifer through the confining layer into the confined aquifer probably occurred during the 1960's, a period when supply wells completed in the confined aquifer by the Vitro Chemical Company were pumped. The Vitro Chemical Company wells have not been pumped since 1969.

During 1992, the U.S. Department of Energy (1993) revisited the Vitro site in a hydrologic investigation. The investigation included the sampling of ground water from existing and new monitoring wells located within and around the site. The results of the sampling indicate that contamination continues to exist in the ground water in the shallow unconfined aquifer beneath and to the west of the site, with the highest concentrations of dissolved solids near the center of the site (Department of Energy, 1993, p. 25). Dissolved-solids concentrations in water from the shallow unconfined aquifer below the Vitro site in 1992 (within 45 ft of land surface) as reported by the U.S. Department of Energy (1993, tables 3.2 and 3.3) are shown in figure 10b. The distribution of dissolved solids in the shallow unconfined aquifer indicated by data collected in 1992 by the U.S. Department of Energy varies from the distribution of dissolved solids in that area indicated by Thiros (1995, fig. 12) that is shown in figure 8. The distribution of dissolved solids shown in figure 8 was defined on the basis of water samples collected from wells in 1983 (Thiros, 1995, fig. 12 and table 1). These wells were not resampled as part of the U.S. Department of Energy (1993) investigation.

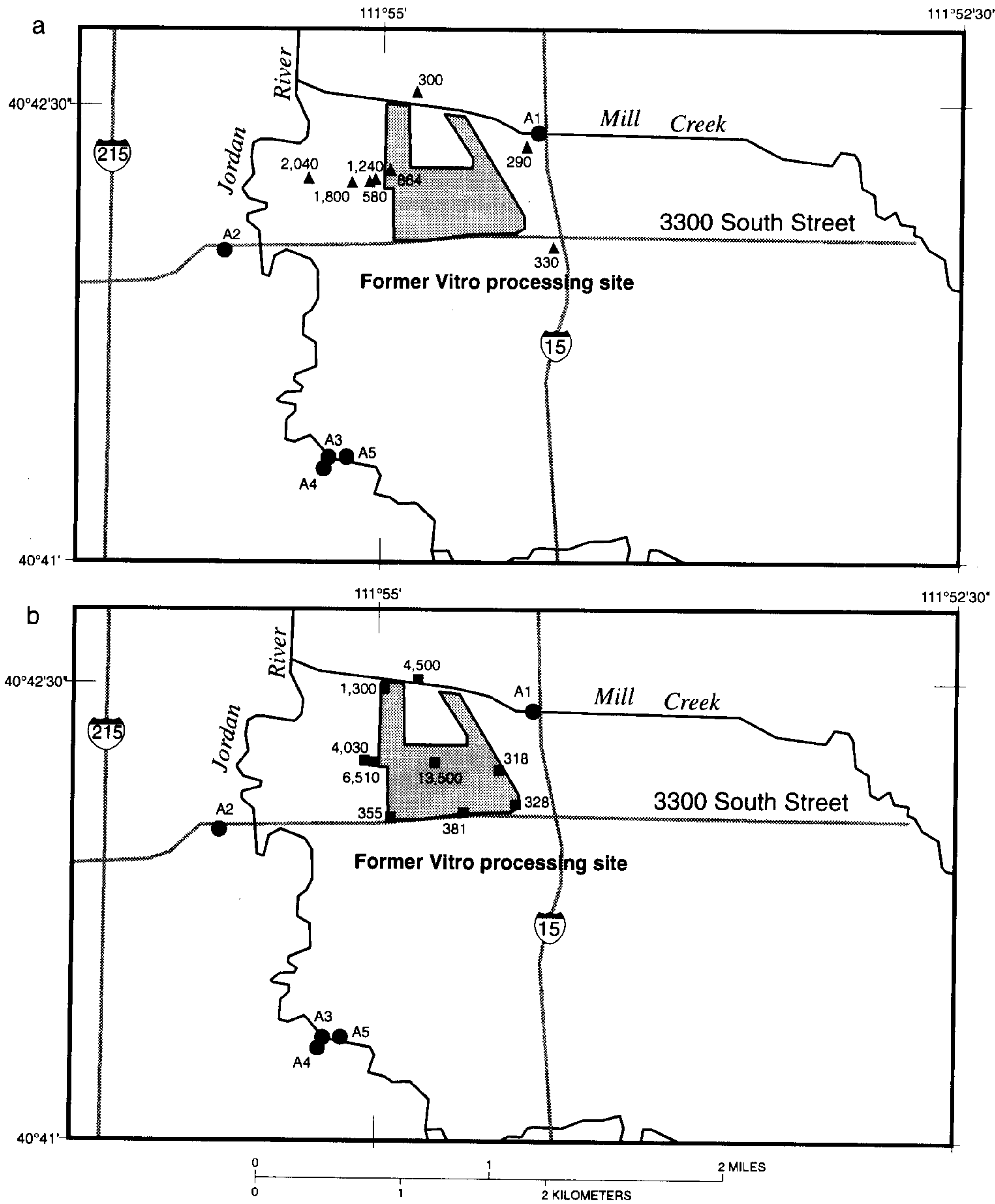
Ground water withdrawn from the upper sediments of the confined aquifer where Waddell and others (1987b) identified possible contamination has not been sampled by the U.S. Department of Energy or the U.S. Geological Survey since the study by Waddell and others (1987b). Thiros (1995, pl. 2) defines concentrations of dissolved solids in ground water in the principal aquifer beneath the Vitro site to range from 250 to 500 mg/L (fig. 7). The distribution shown in figure 7, however, is based on a set of samples that does not include the 1982-83 data cited by Waddell and others (1987b). Analyses of samples collected by the U.S. Department of Energy (1993, attachment 5) from two wells finished in the confined aquifer directly east of the site, and one well finished in the confined aquifer to the north of the site, did not indicate contamination. However, because ground water in the shallow sediments of the confined aquifer beneath and directly west of the Vitro site have not been sampled recently, it is unknown whether ground water with elevated levels of dissolved solids still remains there.

Presently, downward migration of ground water from the shallow unconfined aquifer is prevented by an upward vertical hydraulic gradient between the shallow unconfined aquifer and the underlying confined aquifer (U.S. Department of Energy, 1993, p. 23; Anderson and others, 1994, fig. 13). The potential for downward migration of contaminated water in the shallow unconfined aquifer exists, however, if the water level in the confined aquifer declines such that the direction of flow between the two aquifers reverses.

Southwestern Salt Lake Valley

Four wells in southwestern Salt Lake Valley (table 2 and fig. 7), northeast of Copperton, were selected for analysis. The wells currently are owned and operated by West Jordan City. Three of the four West Jordan City wells were constructed after 1985, and total annual discharge for the well set has increased from 2,085 acre-ft from one well in 1987 to an average of 6,570 acre-ft from four wells for 1992-93. Total annual discharge for the well set has been projected to increase to about 9,900 acre-ft by 2025 (table 2). These increases were not incorporated in the particle-tracking analysis because of the magnitude of resulting drawdowns near the wells. Instead, discharge from the well set was specified at 1992-93 average rates in the 50-year flow-model simulation incorporating projected increased pumpage.

The wells discharge water from the deep unconfined zone of the principal aquifer in an area characterized by dissolved-solids concentrations that range from 500 to 1,000 mg/L (figs. 7 and 9). The wells, however, are located directly north of an area of contaminated ground water resulting mainly from mining-related activities in Bingham Canyon.



EXPLANATION

▲ 290 **Well sampled during 1982-83**—Value is the dissolved-solids concentration in milligrams per liter as reported by the U.S. Department of Energy (1984, tables D-4, D-5, and D-11) and by Waddell and others (1987b, p. 31 and table 4)

■ 381 **Well sampled during June and July of 1992**—Value is the dissolved-solids concentration in milligrams per liter as reported by the U.S. Department of Energy (1993, tables 3.2 and 3.3)

A1● **Public-supply well used in the particle-tracking analysis**—Letter and number are well designation (table 2)

Figure 10. Dissolved-solids concentration in ground water in the vicinity of the former Vitro processing site, Salt Lake Valley, Utah, in water from the (a) upper sediments of the confined zone of the principal aquifer from 90 to 175 feet below land surface and (b) shallow unconfined aquifer.

Southwestern Salt Lake Valley is the site of the Bingham Canyon Mine, one of the world's largest open-pit copper mines (Kennecott Utah Copper, 1992, p. 7). The mine currently is operated by Kennecott Utah Copper Corporation, a subsidiary of Kennecott Corporation, which, together with its predecessors, has been mining copper and other metals from Bingham Canyon since the early 1900's (Kennecott Utah Copper, 1992, p. 7). Mine waste has been artificially leached in the area since the early 1930's. Evaporation ponds about 4.5 mi east of the mouth of Bingham Canyon constructed prior to 1946 and a leach-collection system that includes reservoirs constructed near the mouth of Bingham Canyon in the early to mid-1960's (Bingham Creek Reservoirs) were used to contain mine drainage and wastewater from the ore-leaching facilities. As a result of seepage from these and other smaller sources, ground water in areas of the principal aquifer between the mouth of Bingham Canyon and the Jordan River about 10 mi to the east has been contaminated (Waddell and others, 1987b, p. 18). Dissolved-solids concentrations exceeding 1,000 mg/L in ground water east of the mouth of Bingham Canyon (figs. 7 and 9) typically are associated with elevated concentrations of dissolved sulfate. An area of dissolved-solids concentrations exceeding 5,000 mg/L directly to the east of the Bingham Creek Reservoirs at the mouth of Bingham Canyon (figs. 7 and 9) is associated with low pH (acid water) and elevated concentrations of dissolved sulfate, and, in areas, with elevated concentrations of trace metals including arsenic, copper, and zinc.

Southeastern Salt Lake Valley

Five wells in southeastern Salt Lake Valley between Sandy and Midvale (table 2 and fig. 7) were selected for analysis. These wells discharge from the confined part of the principal aquifer at the west margin of a zone of ground water with dissolved-solids concentrations of less than 500 mg/L that extends from recharge areas to the east (fig. 7). During 1992-93, total annual discharge from the well set averaged about 2,935 acre-ft (table 2). Total discharge from the five wells is projected to increase to about 3,730 acre-ft by 2025. Dissolved-solids concentrations increase in ground water in the principal aquifer immediately to the west of the well set (fig. 7). In addition, ground water with elevated concentrations of dissolved solids and dissolved sulfate, resulting, in part, from seepage of ore-leachate water from evaporation ponds, is present in the upper sediments of the principal aquifer west of the well set on the west side of the Jordan River (fig. 9).

The dissolved-solids concentrations of ground water in the shallow unconfined aquifer are generally greater than the dissolved-solids concentrations of ground water in the principal aquifer in the vicinity of the well set (figs. 7 and 8). A downward vertical hydraulic gradient between the shallow unconfined aquifer and the principal aquifer currently exists in the vicinity of the well set (Anderson and others, 1994, fig. 13), indicating downward movement of ground water from the shallow unconfined aquifer through the underlying shallow confining layer to the principal aquifer.

APPLICATION OF PARTICLE TRACKING

Time-related capture zones for the selected wells were estimated in the following manner: (1) Output from 50-year flow-model simulations incorporating average 1992-93 pumpage and projected increased pumpage, and data defining aquifer geometry and porosity were incorporated into the particle-tracking program, (2) Particles were placed in model cells that simulate discharge from selected wells described in table 2 and tracked backward from the cells toward recharge source areas, and (3) Computed 25- and 50-year pathlines were recorded and used to construct two-dimensional projections of time-related capture zones for selected wells.

MODPATH (Pollock, 1994) incorporates inter-cell flow rates and water levels for all active cells and all time steps stored as output from the 50-year flow-model simulations. The particle-tracking program also requires information defining model-layer thicknesses and aquifer porosity that is not explicitly incorporated in the Salt Lake Valley flow model. Model-layer thicknesses implicitly incorporated in the flow model, discussed earlier in this report, were input to the particle-tracking program. Porosity, however, is not required by the flow model and was estimated for this analysis on the basis of literature values of porosity for unconsolidated sediments compiled by Freethey and others (1994, table 2). On the basis of the compiled literature values, Freethey and others (1994, p. 12 and 15 and fig. 7) estimated that porosity of the sediments in the principal aquifer in southeastern Salt Lake Valley may range from 15 to 35 percent. Literature values included in the compilation by Freethey and others (1994, table 2) indicate that typical porosity values for fine-grained sediments such as the mixtures of silt and clay that compose the shallow confining layer and the shallow unconfined aquifer range from 30 to 60 percent (Davis, 1969, and Bedinger and others, 1986). The scope of this investigation did not include the determination of the spatial variation in sediment porosity throughout the basin-fill aquifer system. Rather, average porosity values were selected from the ranges reported above and assigned to model layers representing different zones of the aquifer system. A porosity of 30 percent was assumed for model layers 3 to 7, representing the principal aquifer. A porosity of 40 percent was assumed for model layers 1 and 2, representing the shallow unconfined aquifer and the shallow confining layer, respectively.

Particles were initially distributed in model cells that simulate discharge from selected wells along the circumferences of three imaginary circles, centered at the cell's center, and with diameters equal to the x-y-axes grid spacing used in the Salt Lake Valley flow model (fig. 11). The circles were oriented horizontally in the cell and spaced equally along the thickness of the cell. Each circle contained 72 particles distributed along its circumference at 5-degree increments. The cylindrical-type positioning of particles within model cells used in this analysis is similar to particle-starting techniques used in other pathline analyses of contributing zones of wells by Shafer (1987) and incorporated in U.S. Environmental Protection Agency wellhead protection area (WHPA) computer programs as discussed by Blandford and Huyakorn (1990). The number of particles required to delimit capture zones is dependent on the complexity of the ground-water flow simulation. During this analysis, the number of particles and the

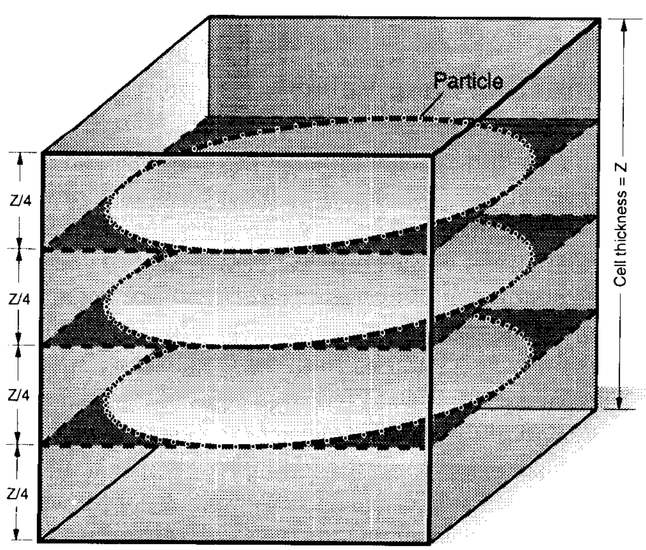


Figure 11. Schematic diagram showing the cylindrical positioning of particles used to compute backtracked pathlines from model cells containing analyzed discharging wells.

number of circles containing particles in model cells was increased, within practical limits, until no substantial change in the resolution of the estimated capture zone was observed. It should be noted that the cylindrical distribution of 216 particles per cell used in this analysis may not be sufficient for similar analyses using different ground-water flow models.

The backward-tracking mode of MODPATH (Pollock, 1994) was used to track particles from their starting positions backward along pathlines toward recharge source areas. Twenty-five- and 50-year pathlines were computed for each particle by starting the particles in time at the middle and end of the 50-year flow-model simulations, respectively. The relation of particle-tracking starting times and flow-model simulation times is shown in figure 12. The 50-year flow-model simulations used in the particle-tracking analysis simulate transient-state flow conditions. Unlike a steady-state simulation, the transient-state flow field can change from time step to time step. Therefore, the location and length of a time-related pathline originating at a given point in space in a transient-state simulation may vary depending on when, during the simulation period, backtracking begins.

During particle tracking, two assumptions concerning the fate of tracked particles were made: (1) All particles started in cells containing perforated intervals of wells used in the analysis were assumed to terminate at those wells as well discharge, and (2) All particles backtracked from their starting cells were assumed to pass through any cell containing a discharging well or other internal sink that does not discharge at a large enough rate to consume all of the water entering the cell. Model cells containing discharging wells or other internal sinks are referred to by Pollock (1989, p. 17-19) as strong-sink or weak-sink cells. In a strong-sink cell, all of the water flowing into a cell is simulated as discharging to the sink. In a weak-sink cell, only a part of the water flowing into the cell is simulated as discharging to the sink. In a weak-sink cell, the volume of flow through the cell that is not captured by the sink cannot be differentiated from the volume of flow that discharges to the sink. Wells for which capture zones were estimated during this analysis were simulated, in many cases, as weak-sink cells in flow-model simulations. The percentage of total flow entering model cells that contain analyzed wells that was simulated as discharging to those wells at the end of each 50-year flow-model simulation is reported in table 3. Because some discharging intervals of analyzed wells were simulated by weak-sink cells in the flow-model simulations, esti-

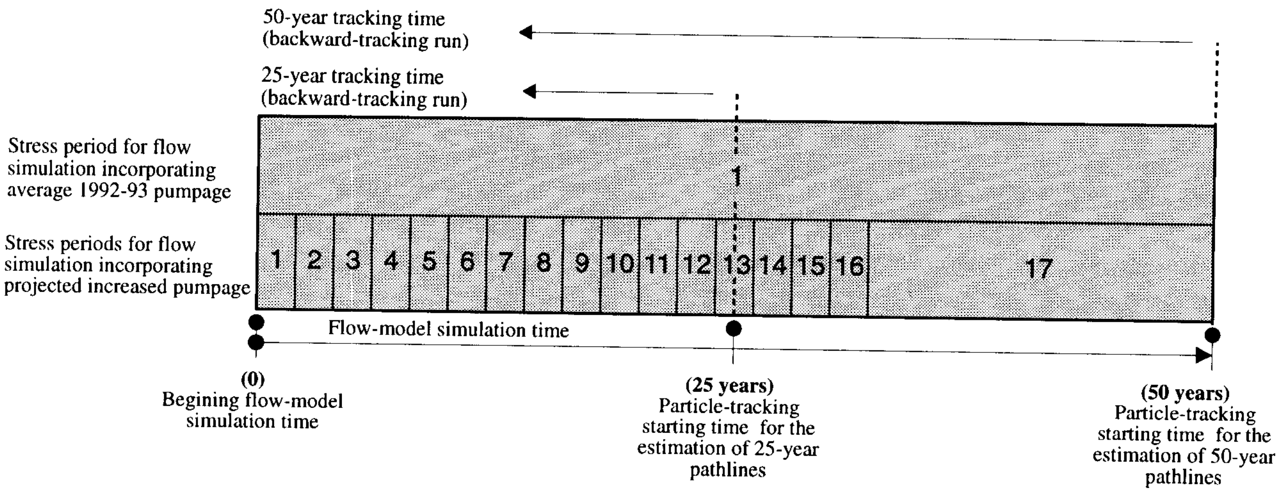


Figure 12. Relation of particle-tracking starting times and flow-model simulation times

mated capture zones of these wells may contain pathlines that, in fact, terminate at other discharge points in the system. This may also be true for estimated capture zones that contain weak-sink cells other than the cells containing wells being analyzed. The significance of this limitation in the analysis is discussed in more detail later in the report.

Twenty-five- and 50-year capture zones, or parts of zones, were constructed and displayed two-dimensionally by projecting computed pathlines onto a horizontal plane (fig. 13). For the purpose of evaluating the extent of estimated zones within different vertical intervals of the aquifer system, parts of zones contained in individual model layers, or groups of model layers, were constructed and displayed separately. The delineation of the intersection of estimated zones with selected model layers allowed for the comparison of those intersections with the distribution of dissolved solids within corresponding layers of the aquifer system. For example, for selected wells discharging from the confined zone of the principal aquifer, the intersection of computed pathlines with model layer 1 can be used to define the part of the capture zone that is contained in that layer. That part of the estimated capture zone then can be compared with the distribution of dissolved solids in the shallow unconfined aquifer represented by model layer 1. A general diagram illustrating the delineation of a time-related capture zone from pathlines and the two-dimensional display of parts of the zone is shown in figure 13. For simplicity, the pathlines shown in figure 13 were backtracked from a single cell containing a set of 3 circles of 30 particles each. The two-dimensional projection of the intersection of a capture zone with a selected model layer need not contain the simulated discharging well. In the example shown in figure 13, particles were started in a cell simulating well discharge in model layer 4 and were tracked backward into model layer 3. Because no particles were started in model layer 3, the part of the zone contained within that layer does not contain the discharging well.

TIME-RELATED CAPTURE ZONES FOR SELECTED WELLS

The following subsections summarize the estimation of 25- and 50-year capture zones of selected wells and the comparison of the spatial extent of estimated zones with the distribution of dissolved solids in the surrounding ground water.

Central Salt Lake Valley

Two-dimensional projections of the 25- and 50-year capture zones within the principal aquifer for the well set in central Salt Lake Valley are shown in figure 14. The results of the particle-tracking analysis based on the simulation of average 1992-93 pumpage and projected increased pumpage indicate that (1) Capture zones for well A1 extend from the well east within the principal aquifer toward recharge areas along the eastern margin of the valley, (2) Capture zones for well A2 extend east from the well within the principal aquifer under the Jordan River, and (3) Capture zones for wells A3, A4, and A5 (contained in the same vertical column of model cells) extend from the wells within the principal aquifer to the west, and to the east under the Jordan River.

Table 3. Percentage of flow into model cells of the Salt Lake Valley flow model containing wells selected for the particle-tracking analysis that is simulated as leaving the cells as well discharge at the end of flow-model simulations

Row and column of model cell simulating well discharge	Model layer of cell simulating well discharge	Well designation (table 2)	Percentage of flow into model cells simulated as leaving the cell as well discharge (end of 50-year simulation period)	
			Flow-model simulation incorporating average 1992-93 pumpage	Flow-model simulation incorporating projected increased pumpage
Well set A, central Salt Lake Valley				
44,44	6	A1	90	75
	7	A1	100	100
45,50	6	A2	43	42
	7	A2	100	100
48,41	4	A3,A4	50	50
	5	A4,A5	100	100
Well set B, southwestern Salt Lake Valley				
66,24	4	B1	100	100
	5	B1	68	69
67,26	4	B2	89	88
	5	B2	100	100
68,26	4	B3	41	40
	5	B3	100	100
69,24	4	B4	51	56
	5	B4	91	91
	6	B4	100	100
Well set C, southeastern Salt Lake Valley				
64,44	3	C1	43	8
	4	C1	99	17
	5	C1	100	17
65,45	3	C2	40	20
	4	C2	75	44
	5	C2	99	57
	6	C2	98	48
66,48	4	C3	47	56
	5	C3	94	98
67,47	4	C4	84	62
68,48	5	C5	68	50
	6	C5	100	95

The comparison of the estimated zones with dissolved-solids concentrations in ground water surrounding the wells as defined by Thiros (1995, pl. 2) indicates that most of the volume of ground water within the zones is characterized by dissolved-solids concentrations of less than 500 mg/L (fig. 14). Twenty-five- and 50-year capture zones for wells A3, A4, and A5 contain ground water from west of the wells with higher dissolved-solids concentrations than water currently being discharged from the wells (greater than 500 mg/L). The 50-year capture zone of well A1, under both pumping conditions, extends to a recharge area at the eastern margin of the valley and contains ground water in that area characterized by dissolved-solids concentrations ranging from 500 to 1,000 mg/L.

The intersection of estimated 50-year capture zones with the upper zone of the confined aquifer (fig. 15) was defined from the set of computed pathlines intersecting model layer 3, which in the area of the analyzed wells is generally simulated as representing sediments from 75 to 225 ft below land surface. The intersection is compared in figure 15 with 1982-83 dis-

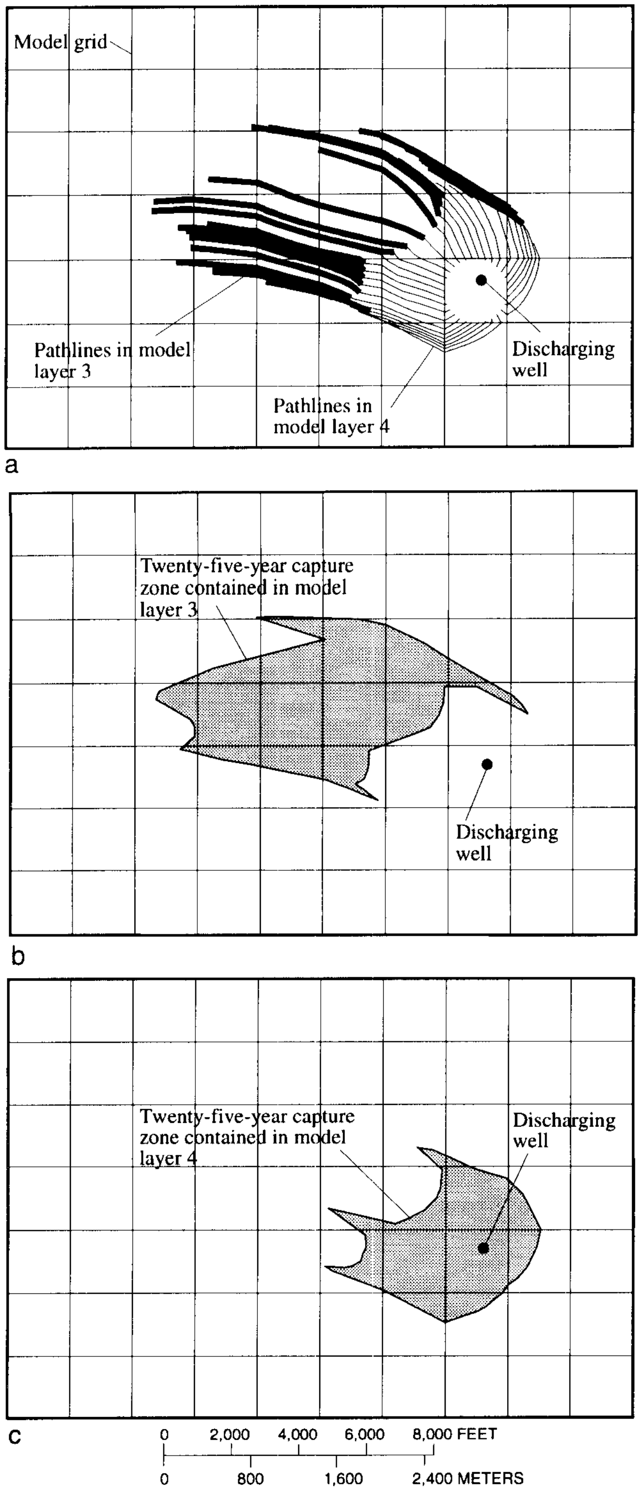


Figure 13. Construction of 25-year capture zone for a single well discharging from model layer 4 in the Salt Lake Valley flow model: (a) Computed pathlines contained in model layers 3 and 4 backtracked from the model cell containing the discharging well, (b) Delineated capture zone contained in model layer 3 defined by the intersection of computed pathlines with that layer, and (c) Delineated capture zone contained in model layer 4 defined by the intersection of computed pathlines with that layer.

solved-solids concentrations in water from the upper sediments of the confined zone of the principal aquifer beneath and to the west of the former Vitro processing site. Only pathlines originating from cells that simulate discharge from wells A3, A4, and A5 intersect model layer 3 in the vicinity of the Vitro site (fig. 15). The zone within model layer 3 extends to near the southern border of the Vitro site but does not include the area beneath or to the west of the site where possible ground-water contamination was sited by Waddell and others (1987b) in 1982-83 water samples.

The intersection of estimated capture zones with the shallow unconfined aquifer (fig. 16) was defined from the set of computed pathlines intersecting model layer 1. No pathlines originating from the analyzed wells intersected model layer 1 in the simulation incorporating average 1992-93 pumpage. Results of the analysis based on the simulation of projected increased pumpage indicate that a relatively small part of the capture zones for wells A3, A4, and A5 is contained in model layer 1 (fig. 16). However, no capture zones for the well set contain the area of contaminated ground water at the former Vitro processing site in the shallow unconfined aquifer. The intersection includes a part of a model cell containing a river boundary that simulates seepage from the river to the shallow unconfined aquifer during the 50-year simulation, indicating seepage from the Jordan River as a possible source of water to wells A3, A4, and A5.

Southwestern Salt Lake Valley

Two-dimensional projections of the 25- and 50-year capture zones within the principal aquifer for the well set in southwestern Salt Lake Valley are shown in figure 17. In this area, ranges of dissolved-solids concentrations in ground water have been mapped for two depth intervals of the principal aquifer: (1) for ground water greater than 300 ft below land surface (fig. 7), and (2) for ground water between 100 and 300 ft below land surface (fig. 9). For the purpose of comparing estimated capture zones with the distribution of dissolved solids in each vertical interval, the intersection of the zones with model layers approximately representing those depth intervals were delineated and displayed separately (figs. 17a and 17b).

The results of the analysis based on the simulation of average 1992-93 pumpage indicate capture zones for the analyzed wells that extend to the west and to the south toward contaminated ground water east of

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Dissolved-solids concentration, in milligrams per liter, 1988-92

- Less than 250
- 250 to 500
- 500 to 1,000
- 1,000 to 2,000

Twenty-five-year capture zone

Fifty-year capture zone

Weak-sink cell within estimated time-related capture zone

Approximate limit of basin-fill material

Public-supply well used in the particle-tracking analysis—Letter and number are well designation (table 2)

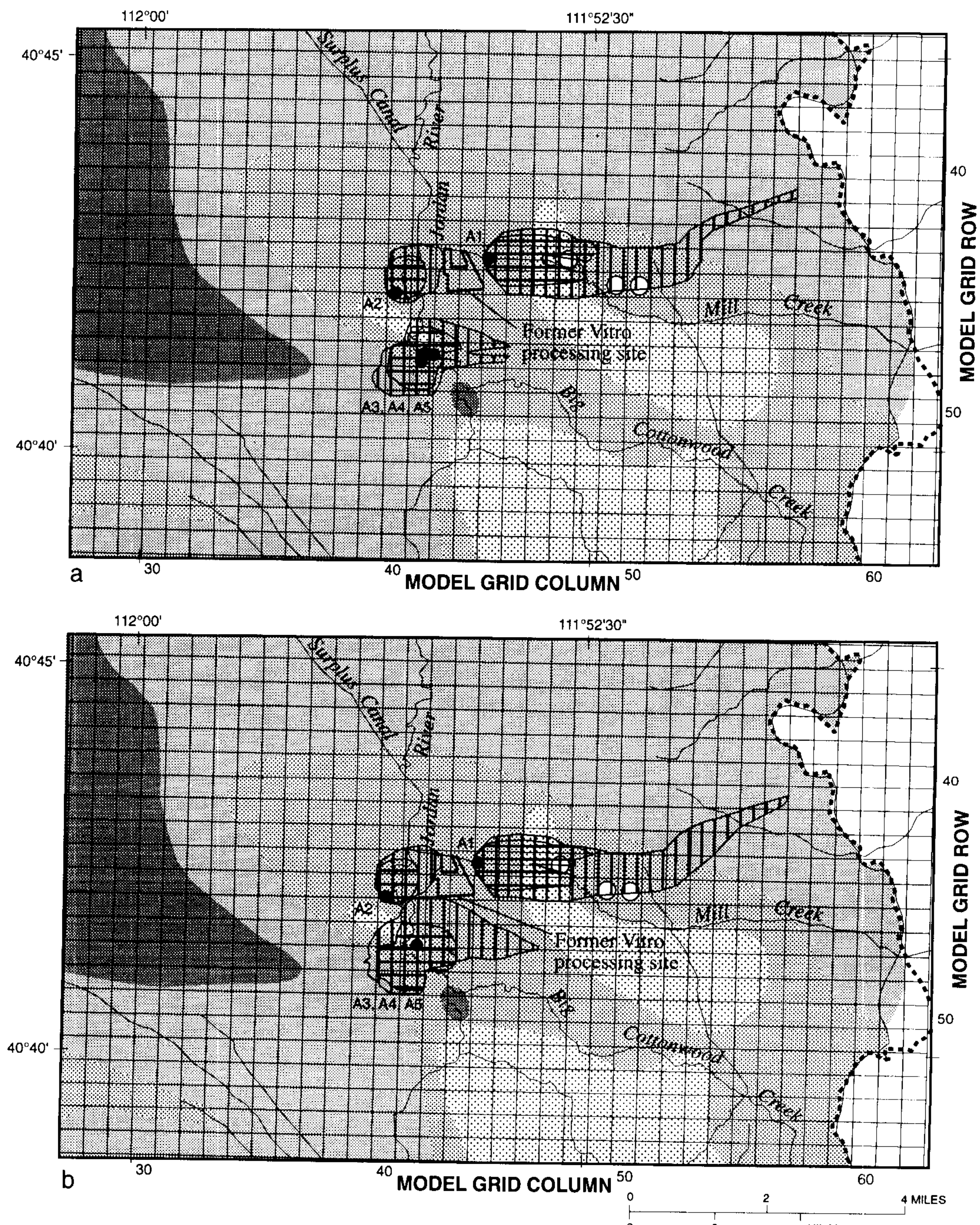
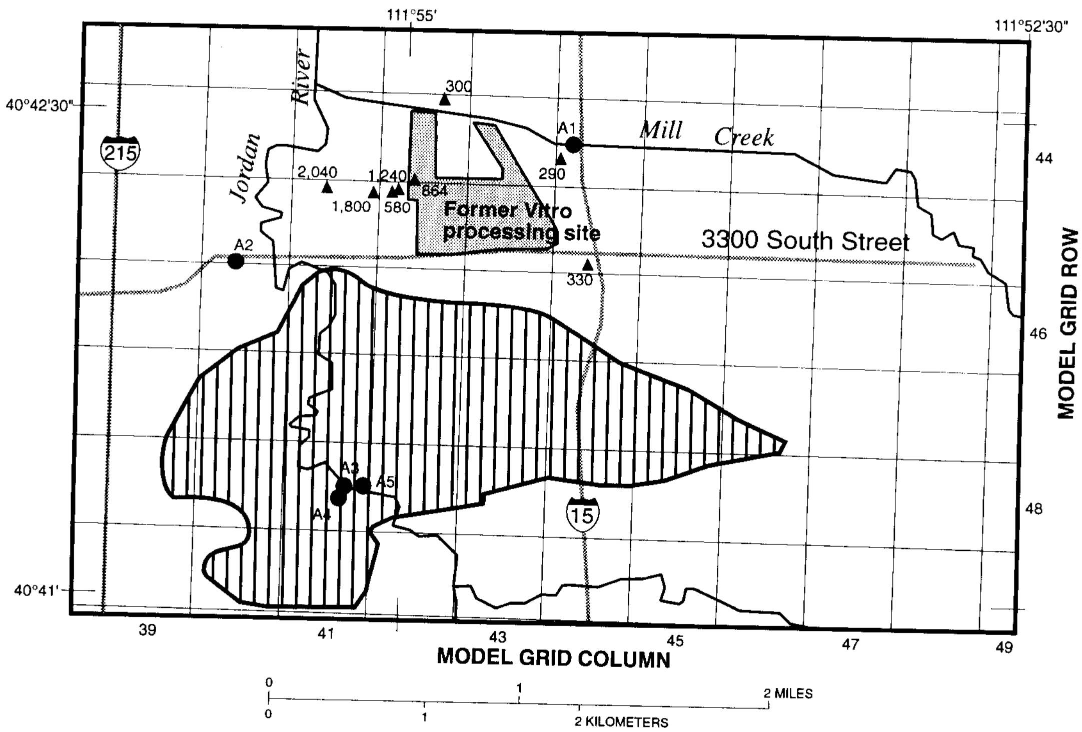


Figure 14. Twenty-five- and 50-year capture zones within the principal aquifer for selected wells in central Salt Lake Valley, Utah, based on the simulation of (a) average 1992-93 pumpage, and (b) projected increased pumpage; compared with dissolved-solids concentration in water from the principal aquifer, 1988-92. Dissolved-solids data from Thiros (1995, pl. 2).



EXPLANATION

Fifty-year capture zone

290 **Well sampled during 1982-83**—Value is the dissolved-solids concentration in milligrams per liter as reported by the U.S. Department of Energy (1984, tables D-4, D-5, and D-11) and by Waddell and others (1987b, p. 31 and table 4)

A1 **Public-supply well used in the particle-tracking analysis**—Letter and number are well designation (table 2)

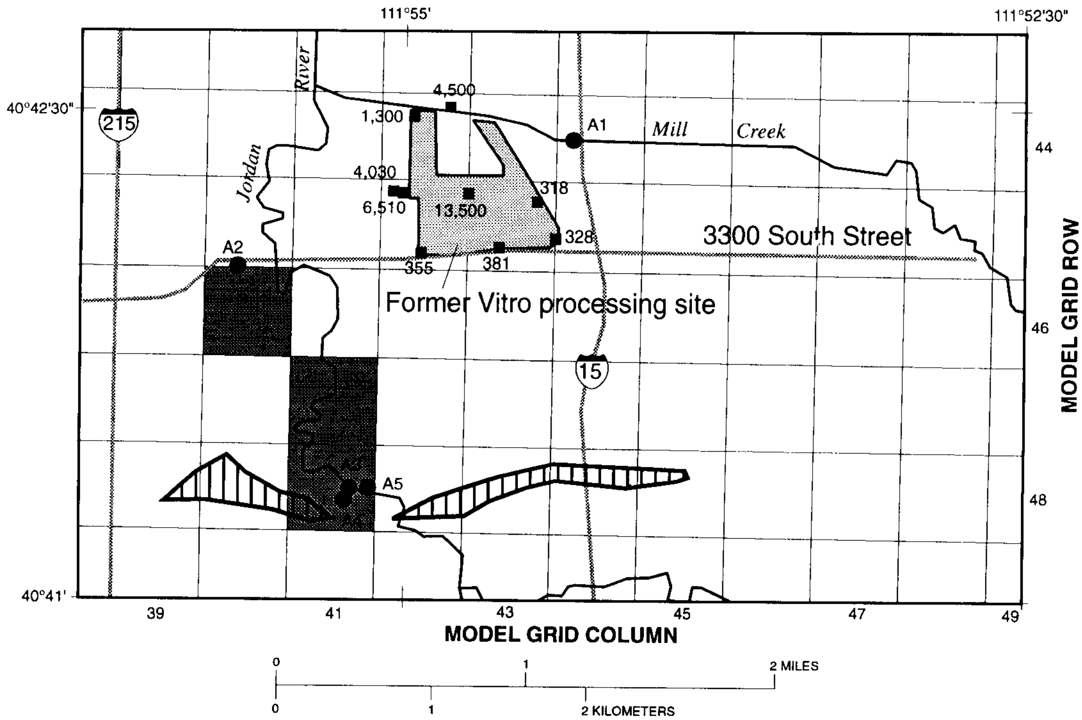
Figure 15. Fifty-year capture zone within the confined zone of the principal aquifer represented in model layer 3 for selected wells in central Salt Lake Valley, Utah, based on the simulation of projected increased pumpage; compared with dissolved-solids concentration in water from the confined zone of the principal aquifer from 90 to 175 ft below land surface at the former Vitro processing site.

the Bingham Creek Reservoirs. Pumpage for this well set was assumed not to increase from 1992-93 average rates in the 50-year simulation incorporating projected increased pumpage, and estimated capture zones based on that simulation are nearly identical to those based on average pumpage shown in figure 17. The 25-year capture zones for the well set contain ground water with dissolved-solids concentrations exceeding 1,000 mg/L (fig. 17). The 50-year capture zones for the well set contain ground water with dissolved-solids concentrations exceeding 5,000 mg/L (fig. 17).

Southeastern Salt Lake Valley

Two-dimensional projections of the 25- and 50-year capture zones within the principal aquifer for the well set in southeastern Salt Lake Valley are shown in figures 18 and 19. Estimated capture zones based on the simulation of average 1992-93 pumpage (fig. 18a) indicate flow to the well set from the south and from the east. Estimated capture zones based on the simulation of projected increased pumpage (fig. 18b) indicate flow to the well set from the south and from the west. The substantial difference in size, shape, and orientation between estimated capture zones based on average 1992-93 pumpage and those based on projected increased pumpage, particularly for 50-year capture zones, is a result of the increase in simulated pumpage from the analyzed wells and from other public-supply wells in southeastern Salt Lake Valley.

For both pumping scenarios, 25- and 50-year capture zones within the principal aquifer contain ground water characterized by dissolved-solids concentrations higher than those of ground water currently being withdrawn from the wells. Movement of ground water from west of the Jordan River toward the well set, as indicated in figure 18b, is particularly significant because of the presence of ground water with elevated dissolved-solids and dissolved-sulfate concentrations



EXPLANATION

River-boundary cell—Simulating seepage from the Jordan River to the shallow unconfined aquifer at the end of the 50-year flow-model simulation

Fifty-year capture zone

381 **Well sampled during June and July of 1992**—Value is the dissolved-solids concentration in milligrams per liter as reported by the U.S. Department of Energy (1993, tables 3.2 and 3.3)

A1 **Public-supply well used in particle-tracking simulation**—Letter and number are well designation (table 2)

Figure 16. Fifty-year capture zone within the shallow unconfined aquifer for selected wells in central Salt Lake Valley, Utah, based on the simulation of projected increased pumpage; compared with dissolved-solids concentration in water from the shallow unconfined aquifer at the former Vitro processing site.

in shallow zones of the principal aquifer directly west of the river (fig. 9). Parts of 50-year capture zones contained in model layer 3, representing the upper zone of the principal aquifer, are compared with the distribution of dissolved solids in the principal aquifer between 100 and 300 ft below land surface west of the Jordan River in figure 19. The comparison indicates that the 50-year capture zone for well C1 extends into an area of ground water west of the Jordan River characterized by dissolved-solids concentrations exceeding 1,000 mg/L. It should be noted that in the flow-model simulation incorporating projected increased pumpage, the model cells simulating discharge to well C1 are weak-sink cells with only a small percentage of total flow to the cells simulated as discharge to the well (table 3).

Although the 50-year capture zone associated with well C1 is defined by pathlines that enter the model cells containing perforated zones of well C1, much of the water entering the cells is actually simulated as passing through the cells and moving toward discharging wells farther east.

The intersection of estimated capture zones for the well set with model layer 1 was delineated and compared to the distribution of dissolved solids in sediments of the shallow unconfined aquifer and the shallow confining layer (within 100 ft of land surface) overlying the well set (fig. 20). No 25-year capture zones intersected model layer 1. Fifty-year capture zones for well C1 and C2 intersected model layer 1 in a small area near the wells (fig. 20).

EXPLANATION

Dissolved-solids concentration, in milligrams per liter, 1988-92—For (a) concentration in water in the principal aquifer between 100 and 300 feet below land surface, and (b) concentration in water in the principal aquifer greater than 300 feet below land surface

- Less than 250
- 250 to 500
- 500 to 1,000
- 1,000 to 2,000
- 2,000 to 5,000
- 5,000 to 48,000

Twenty-five-year capture zone

Fifty-year capture zone

Weak-sink cell within estimated time-related capture zone

Approximate limit of basin-fill material

B1 **Public-supply well used in the particle-tracking analysis**—Letter and number are well designation (table 2)

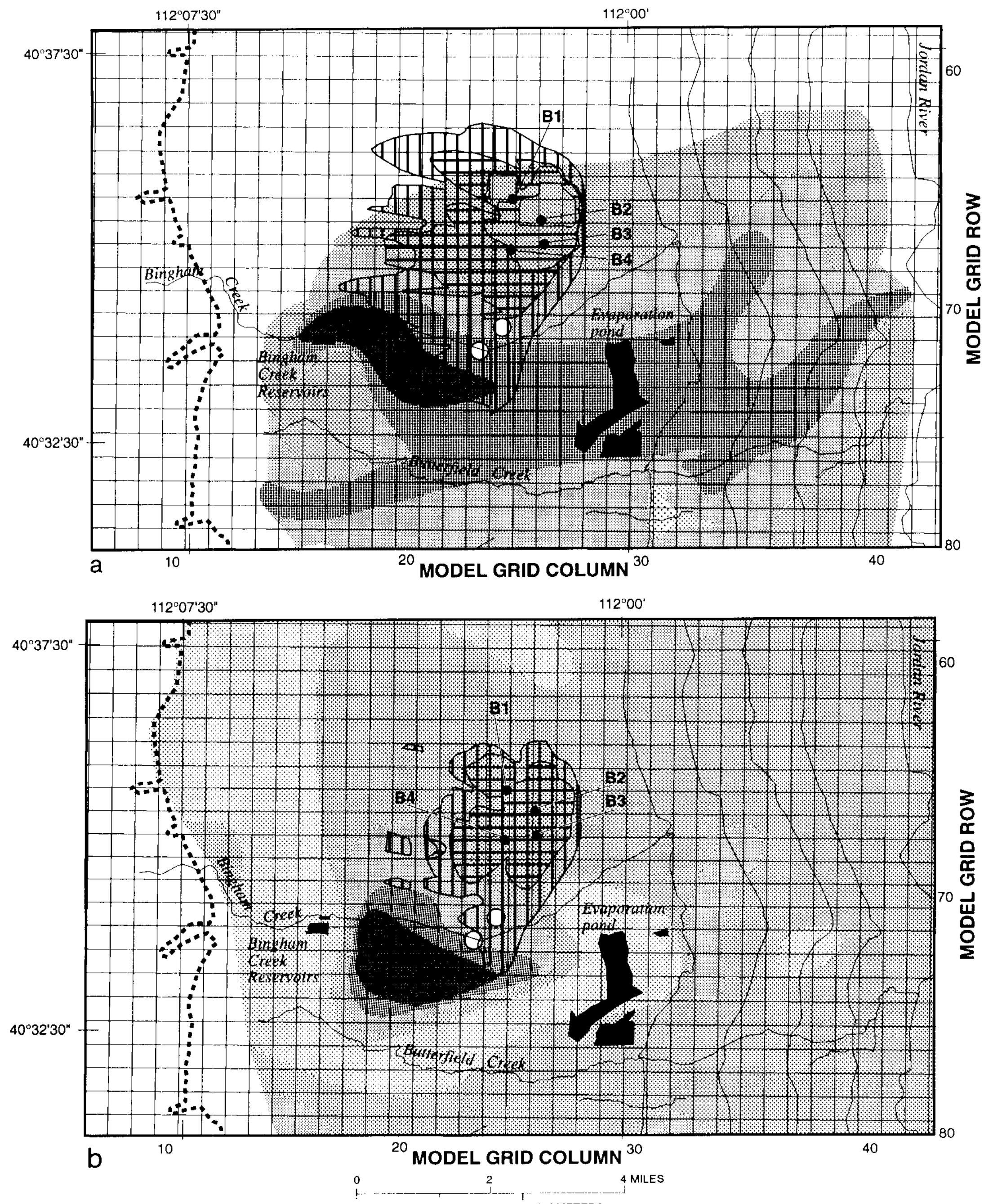


Figure 17. Twenty-five- and 50-year capture zones within the principal aquifer represented in (a) model layer 3, and (b) model layers 4 to 6 for selected wells in southwestern Salt Lake Valley, Utah, based on the simulation of average 1992-93 pumpage; compared with dissolved-solids concentration in water from the principal aquifer. Dissolved-solids data from Thiros (1995, pl. 2).

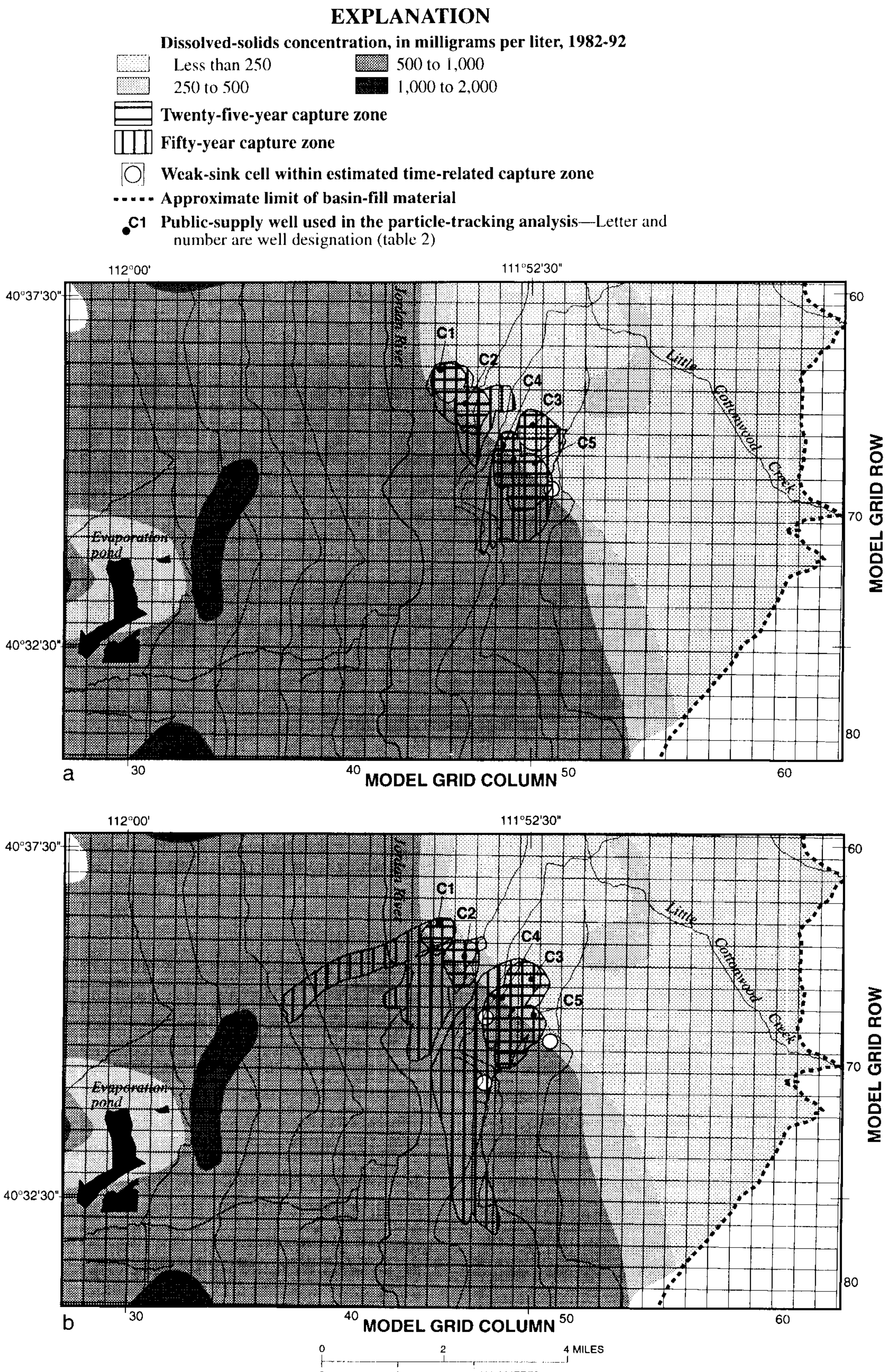


Figure 18. Twenty-five- and 50-year capture zones within the principal aquifer for selected wells in southeastern Salt Lake Valley, Utah, based on the simulation of (a) average 1992-93 pumpage, and (b) projected increased pumpage; compared with dissolved-solids concentration in water from the principal aquifer, 1988-92. Dissolved-solids data from Thiros (1995, pl. 2).

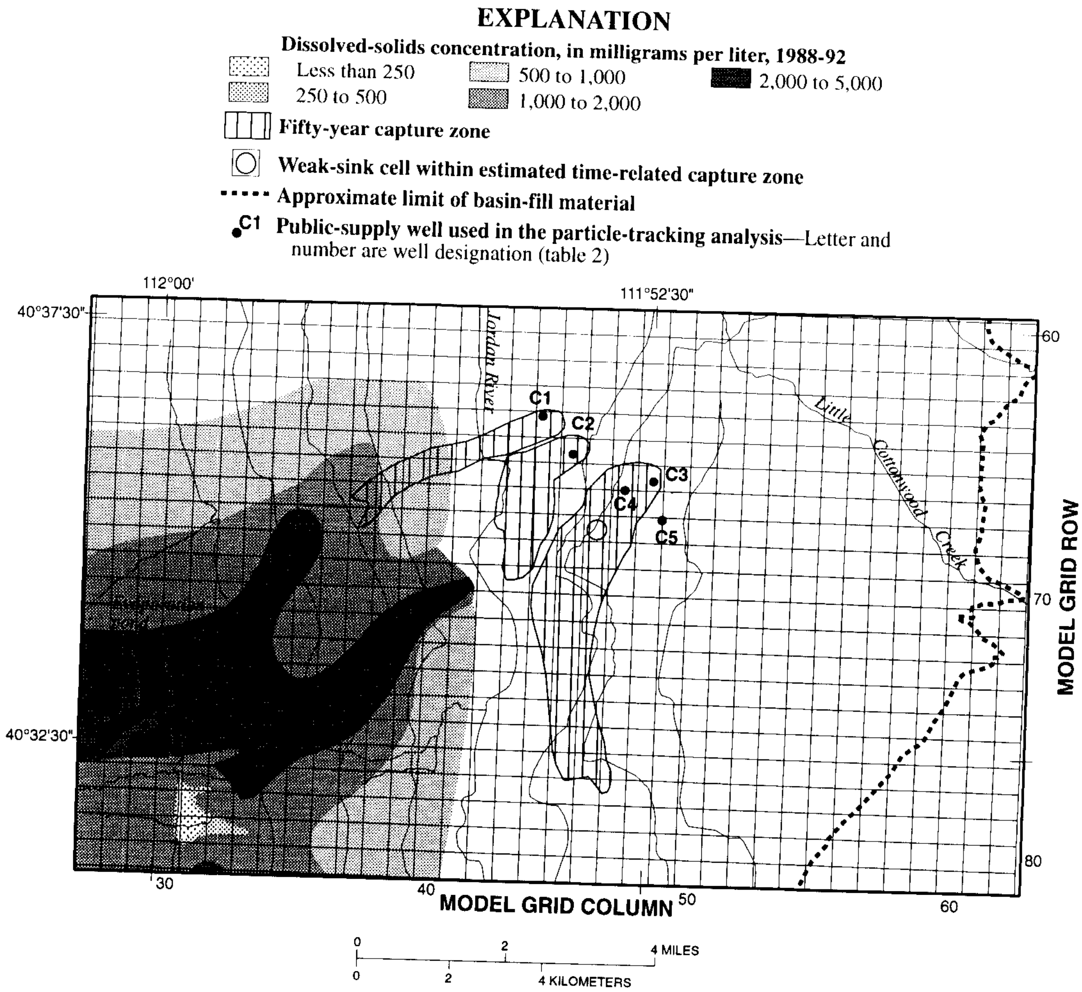


Figure 19. Fifty-year capture zones within the principal aquifer represented in model layer 3 for selected wells in southeastern Salt Lake Valley, Utah, based on the simulation of projected increased pumpage; compared with dissolved-solids concentration in water from the principal aquifer within 100 to 300 feet of land surface, 1988-92.

Limitations and Significance of Estimated Time-Related Capture Zones

The estimation of time-related capture zones of discharging wells can help determine proper use and protection of the ground-water supply. Capture zones are often complex, however, and difficult to conceptualize even in a qualitative manner because of the combined effects of surrounding ground-water sources and sinks and spatial variation in hydrologic properties of the aquifer system. Time-related capture zones can be estimated using a numerical ground-water flow model and a particle-tracking program as demonstrated in this report. Such analyses provide insight into the complexities of the flow fields in the vicinity of discharging wells. The estimated zones, however, are only approximations and are limited by the accuracy of the representation of the actual flow system in the numerical flow model from which they were computed.

Limitations of the particle-tracking analysis that affect the accuracy of the time-related capture zones can be grouped into two categories: (1) discretization effects, and (2) uncertainty in parameters and boundary conditions. An important limitation of the analysis resulting from the spatial discretization of the aquifer system in the numerical flow model is the ambiguity associated with the movement of particles through weak-sink cells. The concept of weak-sink cells in a numerical ground-water flow model has been discussed earlier in this report, and the occurrences of weak-sink cells within estimated time-related capture zones have been identified. As a result of the assumptions made

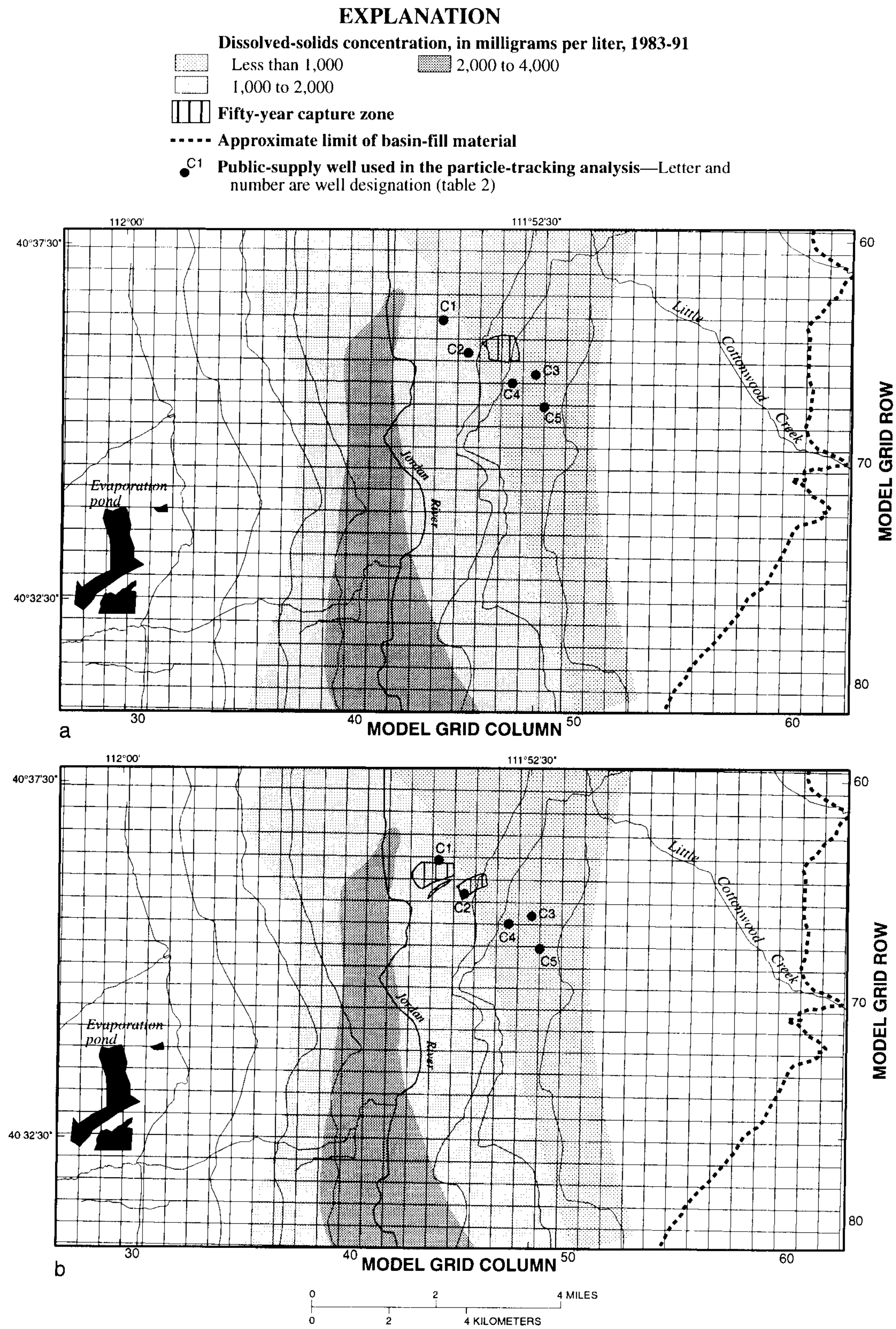


Figure 20. Fifty-year capture zones within the shallow unconfined aquifer for selected wells in southeastern Salt Lake Valley, Utah, based on the simulation of (a) average 1992-93 pumpage and (b) projected increased pumpage; compared with dissolved-solids concentration in ground water within 100 feet of land surface. Dissolved-solids data from Thiros (1995, pl. 3).

during this analysis, estimated capture zones containing weak-sink cells can be assumed to contain pathlines that may not discharge at analyzed wells; therefore, these zones should be interpreted as representing the largest potential volume of the aquifer (maximum potential capture zone) that contains the actual time-related capture zone of the well.

Both the simulation of analyzed wells as weak-sink cells and the occurrence of weak-sink cells in the vicinity of analyzed wells affect the accuracy of estimated capture zones. Well C1 in southeastern Salt Lake Valley (figs. 18 and 19) is an example of an analyzed well simulated in the flow model by weak-sink cells. In the 50-year flow-model simulation incorporating projected increased pumpage, discharge from well C1 decreased from a 1992-93 average rate of 540 acre-ft/yr to 160 acre-ft/yr by 2025 (table 2); simulated discharge from other public-supply wells to the east increased. The result was a substantial decrease in the percentage of flow to model cells containing well C1 that was simulated as leaving the cells as well discharge (table 3). As indicated in table 3, no more than 17 percent of flow entering model cells containing well C1 was simulated as leaving the cells as well discharge at the end of the simulation period. It can be assumed, therefore, that the capture zones estimated for well C1 are artificially large and represent the largest potential volumes containing the actual capture zones. It is impossible, however, to determine in this analysis what part of estimated zones actually contributes water to well C1. In spite of this limitation, the analysis still provides useful, although more qualitative, information about the direction of ground-water flow to the well and the part of the aquifer that may be contributing water to the well in the future.

Well A1 in central Salt Lake Valley (fig. 14) is simulated in the 50-year flow-model simulations by a strong-sink cell in model layer 7 and a weak-sink cell in model layer 6 (table 3). As indicated in table 3, most of the water entering the cells containing well A1 in the flow-model simulations is simulated as leaving the cells as well discharge. The estimated time-related capture zones for well A1, however, intersect weak-sink cells located to the east of well A1 (fig. 14). It should be assumed, therefore, that the estimated zone in the area of the weak-sink cells contains pathlines that terminate at sinks other than well A1.

The representation of internal sinks, and thus the accuracy of pathline computation near them, can be improved by using a finer finite-difference grid. Using smaller model cells may diminish the problem by changing weak-sink cells into strong-sink cells that more accurately correspond to discharge points of all particles entering those cells. From a practical viewpoint, however, when using a regional flow model of a complex ground-water system, it may be impossible to entirely eliminate weak-sink cells.

Limitations of the analysis resulting from the uncertainty in hydrogeologic parameters and boundary conditions used to define the system in the numerical ground-water flow model also affect the accuracy of the estimated capture zones. The ground-water flow model of Salt Lake Valley (Lambert, 1995) used in this analysis is based on mathematical representations of ground-water flow and on a simplifying set of assumptions about the hydrologic system, and, therefore, does not represent completely the complexity of the system. Boundary conditions and hydrogeologic parameters used to define the Salt Lake Valley basin-fill ground-water flow system, and incorporated in the flow model, were developed on the basis of data collected during this and previous studies. Uncertainty in boundary conditions and model parameters was theoretically reduced by calibrating the model to observed historical hydrologic conditions (Lambert, 1995). The resulting set of calibrated parameters incorporated in the final model, however, does not represent a unique solution. Different combinations of data entered into the model might yield similar results. Specifically, two aspects of the model identified by Lambert (1995) may affect the accuracy of estimated capture zones: (1) the uncertainty of estimates of vertical conductivity incorporated in the model, and (2) the simplifying methods used in the model to simulate some components of recharge including recharge from consolidated rock.

Hydraulic conductivity of an aquifer is a function of the aquifer's ability to transmit fluid. Estimates of vertical hydraulic-conductivity values for the shallow unconfined aquifer and the shallow confining layer incorporated in the Salt Lake Valley flow model were based on a probable range of values defined from field data and refinements made during model calibration (Lambert, 1995). A sensitivity analysis of the Salt Lake Valley flow model done by Lambert (1995) indicated, however, that increasing vertical hydraulic-conductivity values for the shallow confining layer and the shallow unconfined aquifer by as much as 50 percent from final calibrated values did not substantially affect the calibration of the model. The results of the sensitivity analysis indicate that it is possible that estimates of vertical hydraulic-conductivity values defined during model calibration and incorporated in the Salt Lake

Valley flow model are artificially low. The uncertainty in estimates of vertical hydraulic-conductivity values used in the flow model could affect the accuracy of the estimated capture zones, particularly for the selected wells in central and southeastern Salt Lake Valley that discharge water from the confined zone of the principal aquifer. For these well sets, if actual vertical hydraulic conductivity of the shallow unconfined aquifer and the shallow confining layer is greater than what is simulated in the flow model, actual parts of capture zones that are contained in the shallow sediments of the aquifer system may be larger than estimated in this analysis.

The simulation of some components of recharge to the basin-fill ground-water flow system has been simplified in the Salt Lake Valley flow model by using specified-flux boundaries. This simplification, particularly in the simulation of recharge from consolidated rock, can affect the accuracy of estimated capture zones in areas were large changes in water levels from starting values are simulated. Recharge from consolidated rock in areas other than the northern end of the Oquirrh Mountains is specified and held constant in the 50-year flow-model simulations used in the particle-tracking analysis. In the actual system, however, flow from the consolidated-rock aquifer to the basin-fill aquifer is head dependent; controlled by the difference in water level between the two aquifers and the hydrologic properties existing at the contact between the two aquifers. In the actual system, large water-level declines in the basin-fill aquifer near the margins of the valley may cause inflow from the consolidated-rock aquifer to change in response. This limitation may affect the accuracy of estimated capture zones of wells in southwestern Salt Lake Valley because of the large water-level declines simulated in that area in flow-model simulations used during the analysis (fig. 5). Temporal variation in recharge from consolidated rock in this area in response to declining water levels may complicate flow paths and travel times to nearby wells.

Although aquifer porosity is not incorporated in the ground-water flow model of Salt Lake Valley, estimated porosity values are specified in the particle-tracking program and are used in the computation of particle movement and pathlines. Uncertainty in the porosity values used in this analysis affect the accuracy of the estimated capture zones. As discussed previously, estimates of aquifer porosity used in this analysis were selected from probable ranges of values for basin-fill material. Based on the defined probable ranges of porosity values for different sections of the aquifer system presented earlier, actual aquifer porosity may differ by as much as 50 percent from estimated values used in this analysis. Particle velocities along pathlines that define well capture zones are inversely related to aquifer porosity. Therefore, if the actual porosity of the aquifer in an area of one of the analyzed well sets is smaller than the estimated values used in this analysis, the actual capture zones for that well set may be larger than estimated in this analysis. Conversely, if the actual aquifer porosity is larger than the estimated values used in the analysis, the actual capture zones for the well set may be smaller than estimated in this analysis. Also, the specification of porosity in the particle-tracking program was simplified in this analysis by assigning a single value to each model layer, or set of model layers, representing different sections of the aquifer system. Potential variations of porosity within layers that may affect the size and shape of estimated capture zones were not represented in the analysis. Although aquifer-porosity values used in this analysis are reasonable, the accuracy of estimated capture zones could be improved by incorporating in the model a more detailed distribution of porosity based on field measurements.

Besides identifying potential capture zones of selected wells, the results of this analysis illustrate the inherent limitations of the particle-tracking method associated with use of a numerical representation of the regional flow system in Salt Lake Valley. These limitations, however, do not diminish the utility of the method or the usefulness of the results of the analysis, but rather define boundaries for the interpretation of the study results. The weaknesses of the method are balanced, in part, by the ability of the numerical flow model to incorporate the effects of spatial variations in aquifer properties and of a complex network of sources and sinks on capture zones for discharging wells. Although the accuracy of the analysis is limited by the effects of discretization and by uncertainty in flow-model parameters, the method proved useful in estimating maximum potential capture zones for selected wells under current and projected future pumping conditions. Obtaining a more detailed and more accurate estimation of capture zones for wells in Salt Lake Valley using a similar approach would require the development of flow models of subregions of the system using a finer finite-difference grid. This approach, however, would not eliminate the limitations of the analysis resulting from the uncertainty in model parameters.

Most of the estimated capture zones for selected wells in this analysis contain ground water with higher dissolved-solids concentrations than ground water currently being discharged by the wells. Although it can be considered that the quality of ground water in the estimated zones could eventually affect the quality of water withdrawn by the wells; the estimation of a well's capture zone does not, by itself, provide information quantifying the changes in the quality of water at that well with time. More detailed information on possible future changes in ground-water quality at points of withdrawal could be obtained by simulating the migration of dissolved solids using a solute-transport computer model capable of simulating mechanisms of transport such as dispersion, and the effects of mixing and chemical reactions.

SUMMARY

Salt Lake Valley is the main population and industrial center in the State of Utah. Maintenance of an adequate supply of water suitable for domestic use is one of the most important factors in sustaining the current population and industrial activity and in allowing for continued economic growth. To provide State officials with information concerning the potential movement of poor-quality ground water to points of withdrawal, capture zones for selected public-supply wells in Salt Lake Valley were estimated using a particle-tracking analysis.

Time-related capture zones of selected public-supply wells were estimated using a regional, finite-difference, ground-water flow model of Salt Lake Valley (Lambert, 1995) in conjunction with the particle-tracking program MODPATH (Pollock, 1994). Twenty-five- and 50-year capture zones were estimated for three sets of wells currently discharging water of adequate quality for public use but located near zones of ground water with high dissolved-solids concentrations or contaminated ground water resulting from human activities. Time-related capture zones were estimated based on 50-year transient-state flow-model simulations incorporating two sets of pumping conditions: (1) constant pumpage representing current average rates of withdrawal as defined by 1992-93 reported values, and (2) variable pumpage representing projected future increases in ground-water demand. The quality of ground water within estimated capture zones was evaluated by comparing the horizontal and vertical extent of the zones with the distribution of dissolved solids in ground water surrounding the selected wells.

The results of the flow-model simulations were incorporated in the particle-tracking program to estimate time-related capture zones for (1) a set of five wells in central Salt Lake Valley near the former Vitro chemical-processing site, (2) a set of four wells in southwestern Salt Lake Valley northeast of Copperton, and (3) a set of five wells in southeastern Salt Lake Valley between Sandy and Midvale. Selected wells in central Salt Lake Valley discharge from a zone of ground water with low dissolved-solids concentrations that extends from the eastern margin of the valley, but the wells are in the vicinity of contaminated ground water associated with leached mill tailings at the former Vitro processing site. Selected wells in southwestern Salt Lake Valley are located directly north of an area of contaminated ground water resulting mainly from mining-related activities in Bingham Canyon. The five selected wells in the southeastern part of the valley are located at the western margin of a zone of ground water with low dissolved-solids concentrations that extends from recharge areas at the eastern margins of the valley. Dissolved-solids concentrations increase, however, in ground water directly to the west of the well set. Ground water with elevated levels of dissolved solids and dissolved sulfate, resulting in part from seepage of ore-mining leachate water from evaporation ponds on the west side of the valley, is present in the principal aquifer west of the wells and the Jordan River.

Particles were placed in model cells containing perforated intervals of selected wells and tracked backward from the cells toward recharge-source areas. Twenty-five- and 50-year pathlines were recorded and used to construct two-dimensional projections of time-related capture zones for each well set.

Two-dimensional projections of estimated capture zones were compared with the distribution of dissolved solids in ground water in the vicinity of the analyzed wells. Results of the analysis of selected wells in central Salt Lake Valley indicate that most of the volume of ground water within the estimated capture zones is characterized by dissolved-solids concentrations of less than 500 mg/L and do not contain the area of contaminated ground water beneath the former Vitro processing site. The results of the analysis of selected wells in southwestern Salt Lake Valley indicate ground-water movement to the wells from a zone of contaminated ground water characterized by elevated concentrations of dissolved solids and dissolved sulfate located east of the Bingham Creek Reservoirs. Fifty-year capture zones for the well set in southwestern Salt Lake Valley extend to the south toward contaminated ground water east of the reservoirs and contain ground water with dissolved-solids concentrations exceeding 5,000 mg/L. Results of the analysis of selected wells in southeastern Salt Lake Valley indicate

that 25- and 50-year capture zones contain ground water with higher dissolved-solids concentrations than ground water currently being discharged by the wells. Fifty-year capture zones for the well set, based on the simulation of projected increased pumpage, indicate flow to the well set from west of the Jordan River.

The occurrence of weak-sink cells in flow-model simulations resulted in some estimated capture zones that contain pathlines that may not terminate at the analyzed wells. Estimated capture zones that originate at or contain weak-sink cells should be interpreted as representing the largest potential volumes of the aquifer (maximum potential capture zones) that contain the actual capture zones. This limitation in the analysis could be corrected, in part, by using a finer finite-difference grid to convert weak-sink cells to strong-sink cells that more accurately correspond to discharge points of all particles entering those cells. However, when using a regional simulation of a complex flow system, it may be impossible, from a practical view point, to discretize the system to the degree necessary to eliminate all weak-sink cells. Although the accuracy of the analysis is limited by the effects of discretization and by uncertainty in flow-model parameters, the method proved useful in estimating maximum potential capture zones of selected wells under current and projected future pumping conditions. Obtaining a more detailed and more accurate estimation of capture zones of wells in Salt Lake Valley using a similar approach would require the development of localized flow models of subregions of the system using a finer finite-difference grid. This approach, however, would not eliminate the limitations of the analysis resulting from the uncertainty in model parameters.

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